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AF INSTITUTE OF TECHNOLOGY

THE INTEGRATION OF ARTIFICIAL INTELLIGENCE TECHNIQUES TO IMPROVE THE EFFECTIVENESS OF ELECTRONIC COUNTERMEASURE STRATEGIES IN A TACTICAL ENVIRONMENT

THESIS

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Captain, USAF

AFIT/GCE/ENG/87D-7

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

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Requirements for the Degree of

Master of Science in Computer Engineering

Barry E. Mullins, B.S.

Captain, USAF

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Preface

The purpose of this research was multidimensional. The first dimension included upgrading the tactical mission planner (TMP) developed by Major Robert Bahnij and Lieutenant Jeff Bradshaw. The tactical mission planner is now a third generation product. Bahnij formed the foundation. Bradshaw extended the TMP to include more realistic information about the domain. The upgrade developed in this thesis effort includes a more realistic representation of the threat environment.

The second dimension of this thesis is the implementation of artificial intelligence techniques. These techniques include constraint-directed search, knowledge-based simulation, and reasoning under uncertainty.

The third dimension of this thesis is the assessment of the research being conducted by Dr. Paul Cohen of the University of Massachusetts at Amherst. Dr. Cohen's research involves reasoning about uncertainty and has produced the tool called MU (managing uncertainty).

I would like to express my gratitude to Major Steve Cross for providing this thesis with all the right 'mix-ins'. Major Cross, my thesis advisor, provided this thesis with the 'flavors' required to whet my appetite for a successful thesis. I would like to thank Major Cross for

his support and ideas. Not only did he know when to 'prune' ideas from the thesis but he also provided an ideal work environment. I am extremely thankful for the latter. Thanks are also in order for arranging funding for the TDY to UMASS and the active interest in my follow-on assignment to Eglin AFB.

I would also like to thank Dr. Paul Cohen for allowing me to visit his lab and perform a portion of my research amongst the EKSL group. I would like to express my appreciation to Paul and the EKSL group, especially Mike Greenberg, David Day, and Jeff Delisio, for their patience while I learned MU. Thanks for the sight-seeing tips, the computer museum, and the directions to Steve's ice cream where I sampled a few 'mix-ins'. Their hospitality is greatly appreciated.

I would like to thank my committee members, Major Phil Amburn and Captain Randy Jost, for providing valuable directions in addition to their support.

Kevin Geiger and Lt Greg Cook of the Electronics Warfare Division of the Avionics Laboratory were a great help during this thesis. They provided the EW insights and help educate me on the finer points of EW. I appreciate their interest in this thesis and their support.

Jeff Mee of Texas Instruments was a tremendous help during this thesis effort and for this I am grateful. Also, David Doak provided excellent support for this thesis. I thank Dave for his support.

My greatest thanks are due my wife Hayley. Her tremendous love, understanding, patience, and support made my studies at AFIT bearable. I promise to return all those late hours I spent away from her while I completed this thesis.

I dedicate this thesis to the loving memory of my mother. Without her and my father's love and support during my undergraduate work, I would not been able to complete my degree. My deepest regret is that my mother was not able to see me graduate AFIT.

Barry E. Mullins

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Abstract

A ground-based tactical mission planning system is presented which increases the situational awareness of a pilot planning an Offensive Counter Air attack mission (air-to-ground). The system increases the situational awareness by automating many labor-intensive tasks associated with tactical mission planning such as fuel and time calculations. This allows the pilot to concentrate on the primary objectives of the mission. This system also provides a rich development environment for an electronic warfare (EW) engineer designing new electronic countermeasure (ECM) strategies by providing facilities to alter ECM resources. The system incorporates artificial intelligence (AI) techniques to increase the user's understanding of the threat environment and how to effectively apply ECM techniques to maximize the probability of a successful mission. It accomplishes these tasks by determining the effectiveness of a mission plan or a new ECM strategy.

Planning a tactical mission is best performed using interactive means to increase the situational awareness of

the pilot by keeping him in the planning process. Similarly, ECM strategies are best developed in an interactive mode to allow the engineer the greatest degree of design freedom. However, these two individuals are only capable of exploiting local knowledge of threats (e.g. constraints about the most effective ECM strategy to use against threats). Consequently, global knowledge about the domain is not available to guide the planning process. Additionally, the inherent uncertainty of threat intelligence data complicates the planning process.

This thesis is an investigation of the novel integration of four explored ideas to produce a system that addresses these problems. These ideas are:

1. a prototype, interactive, ground-based, tactical mission planning system developed for F-16 pilots of the 17th Air Force (Bradshaw, 1986),

2. an ECM strategy generation module based on local constraints associated with threats that is patterned after the constraint-directed search techniques applied by Fox for job-shop scheduling (Fox et al., 1982),

3. an object-oriented simulation patterned after ROSS (McArthur et al., 1986) to evaluate the effectiveness of the ECM strategy, and

4) a technique of reasoning about uncertainty (Cohen et al., 1987b) to evaluate the ECM strategy.

This research demonstrates the feasibility of using AI techniques to develop an effective ground-based tactical mission planner.

THE INTEGRATION OF ARTIFICIAL INTELLIGENCE TECHNIQUES TO IMPROVE THE EFFECTIVENESS OF ELECTRONIC COUNTERMEASURE STRATEGIES IN A TACTICAL ENVIRONMENT

I. Introduction

Background

As advances in computer and electronic technologies continue to grow at an exploding rate, the application of these electronic systems also grows. One of the benefactors of these escalating technologies is the Department of Defense. The military has seen an invaluable potential application for these electronic systems and has developed a new type of modern combat. This new form of combat is directly related to the tremendous progression of electronic technology and has influenced the characteristics of warfare to the point that this type of combat is essential in today's conflicts (Gallotta, 1987:5). This indispensable type of combat is commonly known as electronic warfare.

Electronic warfare is the use of electromagnetic energy to prevent the hostile use of the electromagnetic spectrum (Fitts, 1980:1) and when applied effectively, can counteract or suppress the opposition's ability to wage an effective electronic battle. This ability to counteract or suppress the opposition leads to greater mission success probability

and, therefore, is a desirable asset on any military vehicle.

Electronic warfare equipment is often incorporated into single-seat tactical fighter jets in order to increase the probability of successfully completing a mission. The pilot of the aircraft must be able to effectively use the equipment for maximum success. However, the pilot is not always able to dedicate time to the electronic warfare aspect of the mission and sometimes neglects this aspect. The electronic warfare aspect of the mission is typically handled by the electronic warfare officer aboard a bomber or a two-seat fighter. The pilot is not at fault for neglecting the electronic warfare component of the mission. He is being inundated by a myriad of information during the most critical part of the mission -- flying over enemy defenses. The pilot is often operating at the saturation level while penetrating these enemy air defense systems. As a result of this inundation, the pilot must sacrifice or tradeoff some elements of the mission for others in order to maintain a safe level of situational awareness. Since the primary objectives of a mission are to deliver the munitions on time and to survive the mission, the electronic warfare aspect of the mission is frequently jeopardized in favor of the primary objectives.

Another aspect of the overall mission that complicates the decision making process is the inherent uncertainty of the enemy defense systems (Bahnij, 1985). The enemy is certainly not willing to give all information concerning the defenses to the aggressors. The enemy will surely change the defense system configuration periodically in order to try to confuse the penetrating pilot or catch him off guard. The intelligence information provided to the pilot prior to the mission is a best guess of the current configuration of the defenses. The pilot is not certain of the information he is receiving.

This thesis is the third iteration of previous thesis efforts. The first thesis was a Fighter Pilot's Intelligence Aid For Tactical Mission Planning developed by Major Robert Bahnij (Bahnij, 1985). This thesis effort demonstrated the effectiveness of applying artificial intelligence (AI) techniques -- constraint-directed search, knowledge-based simulation, and reasoning under uncertainty -- to the domain of planning a tactical mission. The research culminated with an interactive ground-based tactical mission planning prototype used to off-load many of the computationally intensive tasks associated with tactical mission planning. This allows the pilot to concentrate on "higher level aspects of the mission" (Bahnij, 1985:ix).

Lieutenant Jeffrey S. Bradshaw implemented the second prototype (a unit level interactive mission planning system). Bradshaw's thesis was A Pilot's Planning Aid For Route Selection And Threat Analysis In A Tactical Environment. This prototype was created after noticeable interest was generated by Bahnij's prototype (Bradshaw, 1986). The objective of this thesis was "to design and implement a prototype mission planning system for possible use by an operational squadron in the United States Air Force" (Bradshaw, 1986:2). Bradshaw used Bahnij's prototype as a baseline system and created a prototype system that incorporated upgrades and enhancements recommended by operational fighter pilots.

This thesis was designed to enhance Bradshaw's prototype by incorporating a more realistic electronic warfare representation of the objects and by handling the uncertain information associated with the realm of electronic warfare. Several issues must be addressed in this realm. Among these issues are efficient terrain masking algorithms, effective means of representing and displaying large numbers of threats, and finally methods for representing and reasoning about uncertain environments. The first two issues have already been addressed by other organizations (Air Force Electronic Warfare Center) and AFIT theses (Smith, 1986). However, these research efforts did

not include an explicit representation of the uncertainty inherent in this realm. Thus, the research assumed all information to be certain.

This thesis effort illustrated the significance of reasoning about and with uncertain information. This thesis used Bradshaw's prototype as a baseline and incorporated electronic warfare as well as reasoning about uncertainty. The baseline was expanded to demonstrate the feasibility of applying a simulation to analyze the mission plan. Such a simulation capability would benefit the pilot by providing immediate feedback on the various types of interactions between threats and how the threats might change the configuration of threat environment due to countermeasures. Additionally, the simulation would benefit an electronic warfare engineer by allowing the engineer to view how effective a piece of equipment or a tactic may be in a specific situation. The engineer would be able to construct the desired simulation traits as well as the specific parameters of the item being tested. Of course the simulation would also have the added benefit of keeping testing costs to a minimum by testing philosophies and ideas on the computer before exercising any flight hardware.

Ground-based tactical mission planning is characterized by making critical decisions in short periods of time. The pilot of a tactical aircraft may only have as few as 40 minutes to perform the mission planning required to

successfully complete his mission (Bradshaw, 1986:9). These 40 minutes include briefings from several different sources. The pilot is required to assimilate the briefed information into a mission plan and has limited time to correct any mistakes. Assimilating this information is a labor intensive task best performed by a computer system utilizing artificial intelligence techniques. The computer system would be able to satisfy many of the lower level mission constraints such as fuel consumption and turnpoint selection (Bahnij, 1985:I-4) while allowing the pilot the freedom to plan the overall mission.

The pilot must also consider how to allocate his electronic warfare resources in order to effectively combat the treats given the type and location of the threats are not known with complete certainty. The pilot should have a preconceived plan on how to allocate these resources. This plan should become part of the overall planning process performed before the aircraft leaves the ground.

Problem Definition

This thesis will investigate the feasibility of the integration of previously explored ideas to develop a knowledge-based system to aid human decision making concerning the allocation of electronic warfare resources. The decisions are based on reasoning about the uncertainty of the domain. This is accomplished by developing a test

bed for this feasibility evaluation, proposing an evaluation criteria, designing and testing a ground-based tactical mission planning system including the effective allocation of electronic warfare resources.

Scope

Several types of tactical missions exist (Bahnij, 1985:II-1). For example, a few of these missions include Counter Air (CA), Air Interdiction (INT), and Close Air Support (CAS). Offensive Counter Air (OCA) missions are a subset of CA missions and are primarily designed to gain and maintain "air superiority" (Bahnij, 1985:II-1). The primary purpose of an attack type of OCA mission is to deny the enemy air superiority by destroying his resources that contribute to his superiority. An example of an attack mission is destroying the enemy's petroleum, oil, and lubrication (POL) resources (Bahnij, 1985:II-1). This thesis is limited to the planning and simulation of an attack type Offensive Counter Air (OCA) mission.

This thesis will only be concerned with the allocation of electronic warfare resources. Due to the time constraint placed on this thesis, the research will not attempt to develop a complete system for a specific aircraft. Instead, the thesis efforts will be directed toward a generic aircraft carrying the basic electronic warfare equipment and will incorporate and assess the research being conducted by

Dr. Paul Cohen at the University of Massachusetts on reasoning about uncertainty. To that end, a prototype will be developed to study the feasibility of further efforts in this field.

The complexity of simulating an airborne intercept aircraft is beyond the realm of this thesis; therefore, all threats are ground based. These threats are comprised of two types: surface-to-air missile (SAM) and anti-aircraft artillery (AAA). The term threat is used extensively throughout this thesis and includes not only the SAM and AAA sites but also the early warning radars and the command center sites. Additionally, the complexity of simulating the end game of a threat projectile such as a SAM or AAA fire is beyond the scope of this thesis. Thus, these simulations will not be included in the prototype.

The nature of electronic warfare quickly becomes classified as specific parameters and performance measures are discussed; therefore, this thesis will avoid all classified material in order to present the electronic warfare community with a generic system capable of being upgraded to classified. The distribution of a classified system would be restricted to only a few agencies, whereas an unclassified system could be distributed freely. This would result in the greatest benefit to the electronic warfare community.

Assumptions

It is assumed that the completed prototype will be distributed to interested agencies including defense contractors. This precludes the use of classified data in the prototype. However, the prototype is assumed to be capable of hosting classified data on an appropriately certified computer system once the prototype is distributed. This assumption does not limit the effectiveness of the thesis since the developed system simply uses unclassified data. A conversion to a classified system would simply entail changing data in the knowledge base. This thesis investigated the feasibility of using these techniques using sufficiently robust unclassified problems. The unclassified nature of the problems was based on fictitious data associated with realistic threat parameters. The unclassified information about the threats was obtained from open literature. For example, some of the information included the frequencies of the threats, the lethal range of the threats, and the tracking characteristics (radar or infrared) of the threats. Furthermore, the Soviet doctrine and operational procedures of electronic warfare were gleaned from unclassified sources.

The threat environment is limited to four types of threats: SAMs, AAAs, early-warning radars, and command centers. Furthermore, the number of threats the system can handle is limited to 84. Additionally, two types of ECM

techniques are supported in this research: jamming and expendables. However, the system is capable of handling three forms of expendables (chaff, flare, and decoy) and four forms of jamming. These limitations were used to bound the problem. A more realistic threat environment will typically contain several more threats and ECM techniques thereby increasing the combinatorics of the search. The most significant effect of this increase would be an increase in the search space. This will increase the processing time for the search as well as memory requirements. In fact, if the search space is sufficiently large, a constraint-directed search may not be possible due to memory limitations.

Another assumption of this research is that of demonstrating the feasibility of the research. This is accomplished by demonstrating the applicability of artificial intelligence in general to the domain of electronic warfare. New techniques for reasoning under uncertainty applied to the most critical portion of a simulation is sufficient for determining feasibility of the research. The determination of the most critical portion of a simulation is determined from a requirements analysis.

The reader of this paper is assumed to have a background in artificial intelligence (AI) or at least familiarity with the concepts associated with AI. Excellent sources for an overview of AI principles and methodologies

are Barr, Cohen, Feigenbaum (Barr and Feigenbaum, 1981a,b; Cohen and Feigenbaum, 1982), Nilsson (Nilsson, 1980), Rich (Rich, 1983), and Winston (Winston, 1984). Additionally, the reader should be familiar especially with expert systems and the pros and cons of using expert systems. Hayes-Roth (Hayes-Roth et al., 1983), Klahr and Waterman (Klahr and Waterman, 1986), and Waterman (Waterman, 1986) are excellent sources for the design of and the power of expert systems. The reader would benefit from and is assumed to have a familiarity with the lisp programming language. The interested reader will find the text by Winston and Horn (Winston and Horn, 1984) to be a good introduction to lisp.

An exhaustive description of the techniques employed for electronic warfare is beyond the scope of this thesis and will not be discussed in detail. However, the underlying concepts of these techniques are discussed in a top-level manner in Appendix C to facilitate a better understanding of why electronic warfare is so complex. Therefore, if the reader requires more detail on electronic warfare than what is provided in this thesis, the reader is encouraged to review the following texts. Schleher's text (Schleher, 1986) is an outstanding source of all electronic warfare aspects. It provides the reader with a complete overview of EW and at the same time discusses some of the more important issues in sufficient detail. Fitts, Golden, and Gordon (Fitts, 1980; Golden, 1982; Gordon, 1981) also

are excellent texts in the field of EW. Very detailed explanations of electronic countermeasures are provided in Boyd (Boyd et al., 1973) and Van Brunt (Van Brunt, 1978; Van Brunt, 1982).

Approach

The primary objective of this research is the design, implementation, and evaluation of an interactive ground-based tactical mission planner. The planner will contain a more realistic representation of the threat environment than the previous two planning systems.

The design phase of this thesis effort began with a familiarization of the proposed programming environment to better understand the design task at hand. The researcher learned as much as possible about the expert system tool Knowledge Engineering Environment (KEE 3.0) and the Texas Instruments (TI) Explorer lisp (list programming) machine. The TI Explorer is the target machine for this research effort. The researcher also completed the traditional approach to expert system design (Waterman, 1986); a problem assessment, knowledge engineering, and a tool selection were completed. The researcher also learned the domain of electronic warfare from an electronic warfare engineer, Kevin Geiger, at the Avionics Laboratory and by reading all information the researcher could find on the topic.

Knowledge of the domain of electronic warfare was required during the design phase to understand the complexities of how electronic warfare objects interact.

Bradshaw's thesis was rehosted from the Symbolics 3600 lisp machine to the TI Explorer. Rehosting the software also included enhancing the representation of the various objects and incorporation of a simulation capability. A simulation requirements matrix was also prepared by the researcher in order to organize the desirable attributes of the finished simulation product. This matrix was the foundation for the design of the planner. This matrix is discussed in chapter IV. These activities occurred during the spring and summer quarters, 1987.

The simulation characteristics were implemented in the knowledge-based tool called Managing Uncertainty during the summer, 1987. The researcher traveled to the University of Massachusetts (UMASS) at Amherst for ten days to learn the environment created by Dr. Paul Cohen of the Experimental Knowledge Systems Laboratory (EKSL) at UMASS called Managing Uncertainty (MU). MU is a development environment for building knowledge systems that are capable of reasoning about the uncertainty of a domain (Cohen et al., 1987b). MU has been used to implement a fire fighting knowledge-based system capable of reasoning about the uncertainty of the fire fighting domain (Day, 1987) and to implement a medical diagnosis consultation system to manage the inherent

uncertainty of planning "diagnostic sequences of questions, tests, and treatments for chest and abdominal pain" (Cohen et al., 1987b:2). These knowledge-based systems were developed by the EKSL and were studied in great detail by the researcher to learn how MU was structured. The primary objective was to become familiar with using MU. At the conclusion of the UMASS trip, a copy of MU in load band format (a load band was required due to the large number of specialized utilities developed by the EKSL) was brought back to the Avionics Laboratory to be rehosted on a TI Explorer. MU was then used as one of the foundations on which this thesis was developed.

Since Dr. Cohen's research on reasoning under uncertainty is funded by the Defense Advanced Research Project Agency (DARPA), the Air Force obviously has expressed a strong interest in assessing the applicability of his research to problems found in the Air Force. Additionally, the thesis sponsor is concerned with the early evolution and transition of DARPA-sponsored AI research to industry.

The prototype was subsequently evaluated by Air Force pilots as well as electronic warfare engineers at the Air Force Wright Aeronautical Laboratories. Results of their evaluation are found in chapter V. Conclusions were drawn on the feasibility of further study in this area as well as a technology assessment of Dr. Cohen's methods.

Equipment and Support

The prototype was implemented on the TI Explorer lisp machine running the Knowledge Engineering Environment (KEE) version 3.0 by IntelliCorp and the Flavors package found on the Explorer. The prototype also was implemented using MU, a development environment discussed earlier in this chapter.

The support required for this thesis effort was the electronic warfare expertise of the Electronic Warfare Division of the Avionics Laboratory. The vast knowledge of the EKSL was also required to implement the knowledge-based system using MU.

Thesis Outline

Chapter II of this thesis discusses tactical mission planning in addition to the various aspects of electronic warfare. This chapter also addresses how electronic warfare affects tactical mission planning as well as a summary of related work. The chapter concludes with a discussion on various techniques for reasoning under uncertainty as well as a discussion on the research being performed by Dr. Cohen. Chapter III describes the conceptual design implemented for this thesis. A detailed design is discussed in chapter IV. The system analysis is presented in chapter V. Chapter VI presents the conclusions of the research and offers recommendations for further research.

II. Background and Related Work

Introduction

The Joint Chiefs of Staff issued the JCS Memorandum of Policy 95 in 1965 which detailed the definition of electronic warfare:

> Electronic warfare (EW) is military action involving the use of electromagnetic energy to determine, exploit, reduce, or prevent hostile use of the electromagnetic spectrum and action which retains friendly use of the electromagnetic spectrum (Fitts, 1980:1).

As indicated, this definition is how the United States views electronic warfare. The Soviet Union has a slightly different philosophy concerning electronic warfare. The term commonly used to describe how the Soviet Union controls the electromagnetic spectrum is radio electronic combat (REC). REC was first introduced in the early 1970's and is closely related to electronic warfare (Chizum, 1985:3). However, the difference between REC and EW is significant enough to merit comment. The REC philosophy is one in which EW and reconnaissance are combined "with firepower to limit, delay, or neutralize our use of command and control systems" (Bush, 1987:59). The doctrine dictates destroying one-third of the enemy forces and jamming another third (Bush, 1987:59). The most significant aspect of REC is integration (Chizum, 1985:4). REC has been adopted by the Soviets as the concept that will integrate political ideology and

military strategy by being an integral part of the Soviet military doctrine for all services (Chizum, 1985:4). Since REC and EW are closely related when referring to the activities associated with the electromagnetic spectrum, the term electronic warfare will be used in this thesis to preclude confusing the reader.

The Soviet Integrated Air Defense System (IADS) (Correll, 1987:64) is one of the most extensive in the world (Schleher, 1986:337). This defense system is known to have "7,000 radars for early warning and ground-controlled intercept, 13,000 SAM launchers, 12,000 antiaircraft artillery pieces, and 5,300 fighter-interceptor aircraft" (Correll, 1987:64). The importance of electronic warfare cannot be emphasized enough in this type of environment; EW is essential for the successful penetration of this defense system (Correll, 1987:64). Since the primary mission of tactical aircraft is to penetrate enemy air defense systems, these aircraft must be capable of defending themselves from the myriad of threats currently employed by the Soviet IADS.

The Soviet IADS is controlled by electromagnetic signals commonly referred to as radar. Since radar is used extensively in the defense system and radars use electromagnetic energy, an aggressor aircraft should expect to protect itself by using methods effective against electromagnetic energy. The most effective combatant of electromagnetic energy, and therefore radar, has been proven

to be electronic warfare. Thus, the tactical aircraft of today must be equipped with electronic warfare equipment in order to survive this massive defense system. However, simply possessing the best EW equipment will not guarantee a successful mission. The equipment must be used in an optimal manner to combat the threats. The activation times of the equipment must be carefully planned to insure the threats are countered and the constraints of the aircraft are not violated.

Tactical Mission Planning

Since the threat defense system employed by the Soviets is so massive, any aircraft wishing to penetrate must carefully plan the mission if any measure of success is expected. The researcher understands the significance of meticulous planning for a tactical mission and incorporates an interactive planning system into the research effort. Appendix E discusses the importance of using an interactive planning system for the domain of tactical mission planning. The planning system incorporated into this research is also discussed along with related systems in this appendix.

Planning Limitations. The mission planning aspect of this research is limited to the mission route and a plausible ECM strategy to combat the threat environment. The various components of tactical mission planning are presented in Appendix E. In addition, the tactical fighter

environment is discussed and how situational awareness of this environment is absolutely critical during mission planning. Conventional automation and artificial intelligence issues are also presented in Appendix E as they pertain to tactical mission planning. Finally, some related systems are introduced. However, the generation of a plausible ECM strategy to combat the threat environment was not addressed. The following section addresses this aspect of this research.

The ECM Dilemma

Overview of Electronic Warfare. A commonly accepted philosophy is that the side with the greatest command of the electromagnetic spectrum will emerge as the victor in any modern conflict (Schleher, 1986:1; Fitts, 1980:7; Golden, 1982:viii; Bush, 1987:66). This philosophy emphasizes the importance of electronic warfare. Both the United States and the Soviet Union have been placing increased emphasis on electronic warfare (Fitts, 1980:6-7; Correll, 1987:65). Therefore, electronic warfare is an extremely important element of any conflict and should be used effectively against any enemy. However, before a commander is capable of utilizing electronic warfare to its fullest potential, he must understand the different components of this complex form of warfare.

As the definition of electronic warfare provided by the Joint Chiefs of Staff illustrates, the electromagnetic spectrum is the vehicle by which electronic warfare is conveyed. Controlling this spectrum involves several different actions. These actions are divided into the three fundamental components of electronic warfare based on their intended purpose -- electronic warfare support measures (ESM), electronic countermeasures (ECM), and electronic counter-countermeasures (ECCM). These components are illustrated in Figure 1. Classifying the various elements of electronic warfare into one of these components is not a trivial task in light of the fact that this field is necessarily dynamic to meet the needs of new threats (Schleher, 1986:6). The components shown in Figure 1 are the most common and will be used in this thesis.

The components depicted in Figure 1 are discussed in detail in Appendix C. This discussion includes the definitions of the components, how they are typically implemented, how they are related to each other, and why the use of radar is significant in this domain.

<u>ECM is the Focus.</u> This thesis will primarily focus on the ECM aspect of EW. In other words, the mission planner concentrates on the ECM required to combat the air defense system in order to insure a successful mission. The planner generates an ECM strategy to use against the threats in order to increase the probability of a successful mission.

This will allow the pilot to concentrate on other aspects of the mission thereby increasing the probability of success. The pilot's situational awareness increases.

ELECTRONIC WARFARE BLOCK DIAGRAM

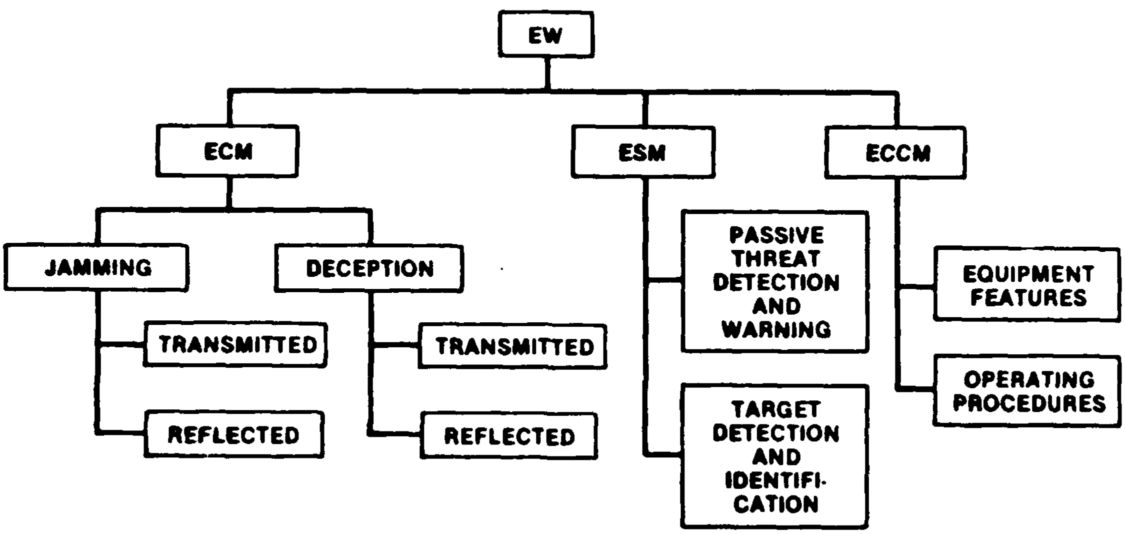


Figure 1. Electronic Warfare Block Diagram
Source: (The Johns Hopkins University, 1986:1-5)

<u>Artificial Intelligence Issues.</u> Generating an ECM strategy to combat the threats is not a trivial task. The researcher does not know of any experts that are able to generate such a strategy. However, this strategy still must be generated. Since experts are not available for this task, a technique other than an expert system will have to be used. As previously noted, the threat environment is

tremendously massive. Therefore, the implemented technique must be able to reason over large numbers of threats effectively. This implies that a weak problem-solving technique, search, should be used to generate the strategy. Additionally, global knowledge about the threat domain are not known. In other words, a heuristic evaluation function is not available to indicate how far the search is from a goal node of the cost of a partial path. Therefore, the local knowledge of the domain, ECM preferences against threats, is used to simplify the search. This local knowledge provides the search with constraints. Therefore, the search is capable of exploiting the local constraints to simplify the search. This search technique is referred to as a constraint-directed search.

Related System. The following system represents a previous effort in the field of constraint-directed search. The search implemented in this research is patterned after the search technique used in this system.

ISIS. ISIS (Intelligent Scheduling and Information System) is a project in which a constraint-directed reasoning system used to schedule the activities associated with factory job-shops was developed (Fox et al., 1982:155). ISIS was initiated in 1980 by the Intelligent Systems Laboratory of The Robotics Institute at Carnegie-Mellon University in conjunction with Westinghouse Electric Corporation (Fox et al., 1982:155; Smith et al., 1986:54)

and has been through several versions during its four year duration. The primary task of ISIS was to develop a schedule for the portion of the Westinghouse Turbine Component Plant (WTCP) in Winston-Salem, North Carolina that was responsible for the production of steam turbine blades (Smith et al., 1986:54). ISIS was implemented in the Schema Representation Language (SRL).

ISIS determines the schedule by performing a constraint-directed search. The ultimate product of the search is a sequence of operations required for each order, the start and stop times, and the resources required for each operation (Waterman, 1986:270). Constraints are implemented into the search in order to limit the complexity of the search. Additionally, a beam search is used as the foundation search algorithm.

Four constraint categories were identified that are used by a scheduler. The first category is organizational goals. These goals are basically to maximize profits. This category of constraints include "job tardiness, work in progress, resource levels, cost, production levels, and shop stability" (Fox et al., 1982:155). All of these factors play a role in the profit margin realized by the company and therefore are considered organizational goals.

The second category of constraints considers the physical limitations of the shop. The schedule cannot

allocate resources (equipment) to an operation if the equipment is not capable of performing the task.

The third category encompasses the prerequisite requirements of the operations. For example, certain operations must be performed before another operation may start.

The preference constraints are the last category. These constraints include any preferences of the supervisor (Fox et al., 1982:155).

As previously mentioned, a beam search is used as the search algorithm. The actual search proceeds in three steps. The first step is defining the search space. This includes defining the constraints that are to be considered during the search.

The second step of the search is searching the search space. However, before the search begins, a set of rules determine the direction of the search and the initial states of the search (Fox et al., 1982:157). The beam search limits the number of states maintained after the application of the appropriate operators. The number of states maintained is controlled by the beam width. Therefore, the search starts at the initial states and after several iterations of applying operators and pruning away the states that are not maintained, a goal state is found. The schedule is the path from a initial state to a goal state (Fox et al., 1982:157).

The last step in the search process is the analysis of the search results. The analysis determines how effective the search was in finding a schedule.

Although the ISIS project uses a constraint-directed search for the generation of a schedule and a post-search analysis to evaluate the effectiveness of the search, the ISIS project lacks the ability to implement the schedule using a simulation. A simulation would verify the validity of the schedule by actually exercising the resources of the shop. Any constraint violations would be apparent during a simulation. This thesis addresses the issue of generating a plan or schedule using a constraint-directed search and then verifying the validity of the plan by performing a knowledge-based simulation of the plan. The simulation also incorporates reasoning with uncertain information.

ECM Strategy Evaluation. Although the ECM strategy is generated using a constraint-directed search, the true effectiveness of the strategy is not known. Some measure of effectiveness must be generated based on the complexity of the EW domain. This complexity prevents a simple calculation to derive an effectiveness. As discussed in this section, the EW domain is comprised of different types of objects that interact with each other in complex manners. The true test of effectiveness can only be found by performing a simulation to allow the objects to interact. This simulation is discussed in the following section.

Simulation

In general, current simulation systems lack the capability to plan. Most simulation systems allow the user to initialize the simulation configuration. Then the simulation is run to observe how the objects of the simulation interact. However, incorporating a planning capability into the simulation should prove to be a powerful asset. Not only will the system plan some aspect of the simulation (ECM strategy for this research) but it will simulate the aspect to verify constraint satisfaction, proper object interaction, or timelines. Therefore, to produce a powerful tool that implements simulation, a planning capability should be included.

Related Systems. The following systems represent previous efforts in knowledge-based simulations as applied to the tactical mission planning domain as well as electronic warfare. These two systems are Simulating Warfare In the ROSS Language (SWIRL) and Tactical Warfare In the ROSS Language (TWIRL).

SWIRL. SWIRL (Simulating Warfare In the Ross Language) is the result of two years of research by the Rand Corp. into knowledge-based simulation which culminated in a prototype air battle simulation. This research demonstrated the payoffs of implementing techniques found in artificial intelligence and expert systems into military simulations (Klahr et al., 1982:iii). "The goal of SWIRL is to provide

a prototype of a <u>design</u> <u>tool</u> for military strategists in the domain of air battles" (Klahr et al., 1982:8). Additionally, the scenario simulated by SWIRL is that of air penetration of offensive forces attacking the enemy in a defensive area. To this end, SWIRL proceeds as follows. After receiving the simulation environment representing the offensive and defensive forces from the user, SWIRL produces a simulation by using the strategies and tactics used by both sides. This knowledge is embodied in the knowledge base. The user of SWIRL is capable of viewing how the simulation progresses with time via an animated graphical interface (Waterman, 1986:295). Also, SWIRL provides an interactive history recording facility to analyze simulation runs in more detail after the simulation is complete.

One of the reasons for developing SWIRL was "to demonstrate the potential and payoff of the ROSS language" (Klahr et al., 1982:ii). SWIRL is written in the ROSS (Rand Object-oriented Simulation System) language. ROSS is an object-oriented language that provides the user the ability to designate the simulation environment using English-like commands (McArthur et al., 1986:73). ROSS is implemented in LISP and is therefore interactive. This asset is valuable to the user when he is able to stop the simulation, survey the current simulation environment and then resume with the simulation. This encourages the user to explore alternatives (McArthur et al., 1986:74). The environment

consists of objects (called actors) and interactions between objects (called message-passing). Each object has two aspects associated with it: memory and behaviors (McArthur and Sowizral, 1981:811). Memory is simply data associated with the static state of the object. Behaviors, as the name implies, describes how the object will behave given the object received a message. This illustrates the message-passing aspect of ROSS. ROSS implements the message-passing capability by maintaining a set of message templates in each actor. Each template has a behavior associated with it such that when the actor receives a message that matches the template, the behavior is activated. ROSS also draws on the benefits of frame-based representation languages. The most predominate feature exploited from these languages is class hierarchies (McArthur and Sowizral, 1981:811). This feature provides means of preventing redundant behavior specifications. The behaviors are inherited.

Although SWIRL and ROSS provide a rich environment in which to simulate air battles, the issue of satisfying the constraints of the ECM resources on board the penetrating platform are not addressed. Also, the selection of the ECM strategy/plan is not discussed. These are significant issues to be dealt with in the electronic warfare domain. A penetrating aircraft is limited in the amount of ECM resources the platform is capable of carrying. The

effective allocation of these resources is an issue that deserves mention. This thesis addresses these issues.

<u>TWIRL.</u> TWIRL (Tactical Warfare In the ROSS Language) was developed by Rand Corp. to further explore the pros and cons of simulating military battles in the ROSS language. (Klahr et al., 1986:225). Briefly, TWIRL is a ground combat simulation developed as a result of the success seen in implementing SWIRL in the ROSS language. The goals of TWIRL were to experiment with the ROSS language, determine a suitable means to depict electronic systems operating on the battlefield, provide a simulation capability for exploring electronic combat strategies and tactics, and finally allow the user to interact with the simulation as it progresses (Klahr et al., 1986:225).

TWIRL simulates a ground battle between a Blue force and a Red force. The emphasis of the simulation is placed on representing command, control, and communications countermeasures (C3CM), electronic warfare (EW), and electronic combat (EC). As with SWIRL, TWIRL provides an animated depiction of the simulation as it progresses over time using color graphics. To provide the greatest insight into the inner workings of the simulation, TWIRL also depicts activity within the electromagnetic spectrum using color graphics.

The hasty river-crossing operation is used for the problem domain. This operation is characterized by the Red

force being on the offensive and crossing a sizable river. This hasty crossing involves "complex interactions and critical timing requirements among the various arms and activities" (Klahr et al., 1986:227).

The developers of TWIRL chose not to develop the electronic warfare strategy using the constraints of the domain. The number and quality of jamming required for the simulation are limited by design (Klahr et al., 1986:229). This presents the problem of constraint satisfaction. The simulation may actually expend all jamming assets early in the simulation leaving one of the units vulnerable. The constraints of the jammers must be considered when creating an ECM strategy. Each player in the simulation has a preplanned schedule (called track plans) that are followed throughout the simulation. This plan does not include the allocation of ECM resources. Allocation is performed only when needed. Once again, this could violate the constraints of one of the units. This thesis addresses the allocation of EW resources using a constraint-directed search of the current assets available to the pilot.

Artificial Intelligence Issues. The field of artificial intelligence that is used to determine the effectiveness of the ECM strategy for this research is knowledge-based simulation. A simulation capability of a mission planning system will improve the situational awareness of the pilot. Since the pilot actually witnesses

how the air defense system will react to his maneuvers, he will obviously have a better mental picture of the task before him. Also, since situational awareness is how the pilot perceives the current situation, he will be better prepared for the mission by observing the simulation results. Knowledge-based simulation is a form of simulation that is driven by the knowledge of how objects interact. Additionally, simulation allows reasoning about possible scenarios designed by the pilot. Simulation represents a powerful method for creating a scenario that is most accepted by the pilot. This involves an iterative process in which the pilot creates a scenario, runs the simulation, and finally modifies the scenario to fit his requirements. Of course, the simulation may cycle through several iterations before the pilot is comfortable with the results. This is one of the true assets of simulation; the pilot is capable of creating a scenario and performing a simulation on it to determine the outcome without flying one minute in the actual aircraft. The same issues can be used to argue for using a simulation during the design phase of EW equipment by an electronic warfare engineer. Thus, a knowledge-based simulation would be capable of providing the pilot with information on how the objects might interact based on the current knowledge contained in each object. This provides a realistic representation of the air defense systems.

Object-oriented programming is another technique used in artificial intelligence that could help the pilot plan his mission. As previously mentioned, the air defense system is composed of several different objects interacting with each other. This supports the philosophy of object-oriented programming. This programming technique represents objects in a structure (frame) within the knowledge base of the system.

For this research, the objects are represented using frames in MU. An example of an object is a SAM 3 site. This object is represented in MU using a frame. The objects interact with one another by sending messages. Typically, the object contains knowledge about what to do when a message is received. For example, if the SAM 3 site receives a message telling it a penetrating aircraft is approaching, the site may respond by turning its radar to the estimated point of entry for the threat. By monitoring the messages being passed between objects, the pilot or EW engineer can obtain a better understanding of the threat environment. Armed with a better understanding of the threat environment, the user can exploit this knowledge to defeat the threats.

Simulation Uncertainty. A certain degree of uncertainty is associated with virtually all knowledge. Knowledge used during a simulation is no exception. This knowledge is usually uncertain. This introduces a new

requirement for simulation systems. If the simulation systems are to truly represent objects and knowledge associated with those objects as realistically as possible, the simulation must be capable of handling reasoning under uncertainty.

The two related systems addressed in this section, SWIRL and TWIRL, do not reason under uncertainty. The implementation tool used for these systems, ROSS, is not capable of handling the uncertainty. The facilities simply do not exist in ROSS. However, uncertainty must be considered during simulation. The next section discusses reasoning under uncertainty and why it is so important for the ECM domain.

Uncertainty

The Uncertain Nature of EW. As discussed earlier in this chapter, two basic types of threats exist in air defensive systems -- surface-to-air missiles and anti-aircraft artillery. One characteristic of the threats intentionally not presented in this chapter is mobility. Most modern threat systems are mobile (Fitts, 1980:81). In fact, the Soviets are constantly striving towards a mobile threat force to better insure weapon survivability (Department of Defense, 1986:57).

One of the effects of this mobile threat force is the pilot must now face an air defense system that has the ability to reconfigure. The pilot must plan his mission based on intelligence information that may be several hours old. Also, the information may not be completely correct due to inaccurate or inadequate electronic reconnaissance (Schlesinger, 1961:164). At best the intelligence information (the world wide electronic order of battle) is updated daily (The Johns Hopkins University, 1986: 4-128). The intelligence information will deteriorate within a short time after initial acquisition. This provides the enemy with an ability to move threats into a new configuration without giving location to the pilot planning the mission. Some threats may be relocated within hours (Fitts, 1980:49-50). Since the pilot will be planning his mission based on old information, he may be making incorrect assumptions about the threats. For instance, he may know that a SAM 9 is relatively difficult to relocate in short periods of time, and the last intelligence update was gathered only two hours ago. He may feel that the SAM 9 on his map has not relocated and set up to a threatening state with a high degree of certainty. The pilot has inferred the certainty of assumption based on known information.

Inferring or reasoning about the uncertainty of the location of the threats is one of the operations the pilot must perform while planning his mission. In order to

alleviate the burden of this reasoning process from the pilot, the computer system should make these inferences based on the current assessment of the threat environment. This thesis attempts to provide such a system.

The air defense system is not the only source of uncertainty during a penetration. A skilled pilot soon learns that an effective means of combatting threats is to respond with uncertainty. For example, if a pilot were to use the same electronic countermeasures consistently in response to a given threat, the enemy will surely detect his pattern and defeat him. Consequently, a pilot should add an element of uncertainty to his ECM responses in order to confuse the enemy as much as possible. Changing the ECM responses is one approach. This forces the threats to consider a larger search space in order to identify the ECM being used thereby giving the pilot precious time to elude the threat.

This type of uncertainty can be planned using artificial intelligence approaches to the problem. A conventional algorithm may provide the pilot with a small degree of randomness but does not bring to bear on the problem the inherent knowledge necessary to reason about the planning process. As the name implies, the result is algorithmic. The result will typically be the same for a given situation. This can hardly be categorized as random and certainly does not inject uncertainty into the air

defense system since the ECM response will be generally the same for each situation. What is needed is a way to plan the mission with knowledge about the threats. This knowledge will include the usual information about a threat as well as the uncertainty associated with each threat. As mentioned earlier, the air defense system will include numerous threats. This creates an enormous search space for the mission planner. Heuristics are commonly used to manage the search (Nilsson, 1980:72). Also, an artificial intelligence approach to the planning process will insure the mission is planned much the same way a pilot might since the knowledge brought to bear on the problem is his coupled with the expertise of electronic warfare engineers. However, the distinguishing difference between the algorithmic approach and the AI approach is the degree of uncertainty provided to the pilot to administer ECM techniques. The AI approach will find a solution to the problem but not necessarily the best solution (Rich, 1983:43). This in itself generates uncertainty for the planning process. The pilot is no longer constrained to using the best and obviously predictable ECM as generated by algorithmic planners.

As this discussion points out, reasoning about the uncertainty of the EW domain is critical to a successful mission plan. The mobility of the threats, the deteriorating intelligence information, and the need to

respond to threats with unpredictable ECM all illustrate the significance of uncertainty in this domain. The following discussion presents some of the issues associated with reasoning about uncertainty and how this research plans to deal with the issue.

Introduction to Reasoning About Uncertainty. In this complex world, nothing is certain. A small, private aircraft piloted by a teenager may penetrate the most sophisticated air defense system in the world. A lisp machine will replace the brain of a pilot flying an F-16 fighter aircraft. Both of these scenarios present what seem to be impossible events. Impossible? The probability of them occurring is remote. However, there still exists the possibility they will occur. The inhabitants of this planet assume these events to be false, but how can they be certain? They cannot! Uncertainty exists in everything.

The field of artificial intelligence (AI) is no exception. Barr and Feigenbaum define artificial intelligence as follows:

> Artificial intelligence is the part of computer science concerned with designing intelligent computer systems, that is, systems that exhibit the characteristics we associate with intelligence in human behavior -- understanding language, learning, reasoning, solving problems, and so on (Barr and Feigenbaum, 1981a:3).

As this definition points out, AI is a science and its goal is to emulate human behavior. Both of these characteristics, science (Shortliffe and Buchanan, 1984:233)

and human behavior, are inherently uncertain by their very nature. Thus, AI must contend with the issues associated with uncertainty.

Recently, the area of AI that has emerged with the greatest amount of success has been expert systems (Hayes-Roth et al., 1983:xi). Donald Waterman defines expert systems as "sophisticated computer programs that manipulate knowledge to solve problems efficiently and effectively in a narrow problem area" (Waterman, 1986:xvii). Since expert systems are a large part of AI, they too must contend with the uncertainty issue. In fact, expert systems should place a concentrated effort on handling the uncertainty.

Expert systems have several sources of uncertainty. This is due to the fact that an expert system "embodies the expertise of one or more experts in some domain" (Waterman and Hayes-Roth, 1983:169). This expertise includes rules of thumb commonly referred to as heuristics (Hayes-Roth et al., 1983:4). These heuristics are educated guesses used to deal with errorful or incomplete data (Hayes-Roth et al., 1983:4). Since the knowledge is provided by experts, the uncertainty of the expert's knowledge must be considered. The experts will sometimes provide information under the pressure of a deadline (Stefik et al., 1983:93). Also, the expert may make judgements based on data that are not complete. Another cause of uncertainty in expert systems is the manner in which the uncertainty is represented in the

system. If a numerical representation is used, the expert is required to supply a degree of belief. The expert may be asked to supply a number that represents more accuracy than the expert's belief (Cohen, 1987a). There are several more causes of uncertainty in expert systems that will not be discussed here. However, the fact remains that expert systems must contend with uncertainty. Expert systems contend with uncertainty by reasoning about the uncertainty in the system.

Representing uncertainty has been addressed by several researchers in a variety of different approaches. Although these researchers have proposed several implementations of representing the uncertainty, only a few basic techniques underlie these various approaches. The reader is assumed to have an understanding of these techniques. However, the well-documented techniques for representing uncertainty used as in the expert system community are presented in Appendix F for the interested reader.

The important issue with reasoning about uncertainty is that the technique being implemented should be able to decide on what to do based on the uncertain information given to the system. The following section is a discussion concerning reasoning under uncertainty and techniques used for this reasoning process.

Reasoning Under Uncertainty. As previously mentioned, the ability to reason under uncertainty is important. The representation techniques provide different means of handling the uncertainty. However, the system must be able to reason under the uncertainty. This implies that a technique is required to determine what to do based on uncertain knowledge. The technique will help an intelligent problem solver decide what to do when it is uncertain. Some of these techniques are presented in the following sections.

Diversification. The first technique discussed is the diversification approach. Diversification allows the system to spread the uncertainty across several hypotheses. This, in effect, allows the degree of required certainty to be manipulated by following a "process in which one trades something one wants for certainty" (Cohen, 1985a:20). If the certainty of the conclusions are not acceptable, the system could be calibrated to acquire the acceptable level of uncertainty. MYCIN (Buchanan and Shortliffe, 1984) is an excellent example of the diversification approach. MYCIN is an expert system, and its

> ... principle task is to determine the likely identity of pathogens in patients with infections and to assist in the selection of a therapeutic regimen appropriate for treating the organisms under consideration" (Shortliffe and Buchanan, 1984:237).

MYCIN often selected a group of treatments based on its uncertainty of the patient's illness (Cohen, 1985a:20-21). Since MYCIN had to provide a recommendation to the

physician, it implemented a diversification approach to cover as many candidate diagnoses as possible with the least number of drugs (Cohen, 1985a:21). The diversification represented in MYCIN is the trade-off between possible side effects of the drugs and the certainty that the drugs prescribed will cure the disease (Cohen, 1985a:21).

Control Approach. The next approach to reasoning about uncertainty is the control approach. The domain in which the expert system is being implemented may in many cases be exploitable in such a way to minimize the effects of uncertainty on the system. This is the basic premise of the control approach. Control is used to "specify what a problem solver should do next" (Cohen, 1985a:42). The control structure commonly implemented is the blackboard. The blackboard concept was first introduced during the development of the HEARSAY-II speech-understanding system (Erman et al., 1980; Cohen, 1985a:44; Rich, 1983:278). HEARSAY-II applies the control approach by applying "selective attention" (Erman et al., 1980:221) to the blackboard. The selective attention is accomplished by a heuristic scheduler. This scheduler is the control mechanism of this system since it tells the system what to do based on its current information. The HEARSAY-II example illustrates the significance of the control approach; this approach is useful "when the goal is to interpret noisy, but converging, evidence" (Cohen, 1985a:43).

MU. MU (Managing Uncertainty) is a tool developed by Paul Cohen to address the problem of what to do based on uncertain knowledge. This section discusses how MU reasons under uncertainty. That is, not only does MU provide facilities to represent uncertainty but it also reasons under the uncertainty. In other words, based on the uncertainty of something, what should MU do next.

One of the more powerful properties of MU is the combining function. The reader should not confuse the pooling combining functions discussed earlier in this chapter with this form of combining function. Pooling combining functions are a way to represent uncertainty whereas the combining function presented in this section refers to functions within MU. Combining functions derive the values of dynamic characteristics of an object (called features) and consequently maintain a current inference network. This is accomplished by propagating values throughout the inference network. The combining function updates the value of the dynamic feature whenever new information becomes available as a result of querying the user or propagation of a new value. Combining functions currently resemble rules.

"MU is a development environment for knowledge systems that reason with incomplete knowledge" (Cohen et al., 1987b:2). As discussed earlier in this chapter, the domain of electronic warfare is complicated with incomplete

knowledge in several areas. For example, the intelligence information the pilot uses during his planning process may contain incomplete information about the threat environment.

MU is an environment for building prospective reasoning systems (Cohen et al., 1987b:1). "Prospective reasoning is a form of planning in which knowledge of the state of the world and the effects of actions is incomplete" (Cohen et al., 1987b:1). In different words, this form of reasoning "involves answering the question 'What shall I do next,' given uncertainty about the state of the world" (Cohen et al., 1987b:14). The domain of EW fits nicely into the realm of prospective reasoning. First, as previously mentioned, not all information about the threat environment is complete. Second, the effects of applying an ECM technique against a threat are not completely known during the planning process. Third, how the threats reconfigure to combat the penetrating aircraft is not completely known. The threats, in effect, work on the question "What shall I (we) do next given what we know and how confident we are with the information."

Cohen uses combining functions to implement his theory of endorsements. In other words, the combining functions act as control elements. These functions assess the current situation and its associated belief to determine what to do next. Therefore, MU not only represents uncertainty but it also, more importantly, reasons under the uncertainty. It

addresses what to do next based on uncertain knowledge. The section titled 'MU Selection' in chapter III provides a more detailed description of MU.

Summary

Electronic warfare is an immensely complex domain. This chapter presented the basic elements of electronic warfare and how these elements interrelate. The true power of EW is the manner in which it is applied. EW is most effective when the individual elements are applied in concert. No one element is sufficient to protect the aircraft. In fact, the pilot must incorporate all elements of EW as well as strategy and tactics to effectively combat the air defense systems of today (Correll, 1987:64). This places tremendous demands on the pilot's cognitive abilities.

The pilot on a tactical mission must be prepared to test his cognitive skills. Since the tactical fighter environment is characterized by astonishing speeds (as much as 600 knots) and very low altitudes (as low as 50 feet), the pilot has precious little time to make life-threatening decisions. Not only must the pilot perform his mission but he must also apply the mentioned actions to combat the enemy's defensive systems. This typically overwhelms the pilot with vast tasks that must be accomplished. The pilot is inundated with information he must assimilate. This

degrades the situational awareness of the pilot and thereby jeopardizes the mission.

A possible solution to this dilemma is to provide the pilot with an intelligent planning assistant. Not another crewmember per se but an intelligent computer system capable of making decisions as an expert would. The pilot would be able to plan his mission at a much higher level of abstraction. He would not have to worry himself with the details of computations. This would increase the pilot's situational awareness by allowing more time to review the mission and perform contingency analysis.

An interactive planner provides the pilot with the ability to select a mission route. However, the pilot must incorporate ECM into the plan to combat the threats encountered on the route.

This chapter has presented some of the ECM considerations of tactical mission planning. Paramount among ECM considerations is the complexity of the EW domain. This complexity complicates the generation of an effective ECM strategy to combat the threat environment. The local constraints of the threats must be exploited to determine a plausible ECM strategy. This is accomplished in this research using a constraint-directed search.

After a plausible strategy is found, the effectiveness of the strategy must be determined to provide feedback to the pilot. Based on this feedback the pilot may decide to

alter his mission route. The effectiveness of the ECM strategy is determined using a knowledge-based simulation. However, the inherent uncertainty of the EW domain dictates that the simulation must reason under this uncertainty.

The mission planning system developed for this research integrates four explored ideas into a planning environment conducive to mission planning with uncertain information and uncertain outcomes. These four ideas include interactive planning, constraint-directed search, knowledge-based simulation, and reasoning under uncertainty. These ideas are integrated to improve the effectiveness of ECM strategies in a tactical environment.

III. Conceptual Design

The tactical mission planning system described in this thesis is primarily targeted for use by two groups of individuals -- the pilot planning an OCA mission and an electronic warfare engineer. As such, the planner must be designed to satisfy both groups. The integration of four explored ideas -- interactive planning, constraint-directed search, knowledge-based simulation, and reasoning about uncertainty -- accomplishes this requirement. The conceptual designs of these ideas are presented in this chapter. However, additional requirements exist for the system and are also discussed.

The researcher understands the significance of working with the end user early in the project. As a result, several meetings with the end user for this system were conducted to insure the prototype will perform as the user wishes. Consequently, a requirements matrix was developed to identify the desired and necessary requirements. The matrix also discusses how an operationally useful system could address the requirements. This matrix is found in Appendix D.

Requirements of the Planner

The ultimate requirement for the finished product is to be usable, accurate, and faster than human planning. These

requirements should exist for all computer systems. However, several additional capabilities/requirements are desirable for this thesis. The following paragraphs illustrate the major requirements desired for the development of a robust prototype. This is not to say the prototype will include all of the mentioned requirements. Since this thesis effort is bound to a fixed time period, the prototype must be properly scoped to an appropriate size. However, each requirement is discussed in detail and will indicate if the requirement is implemented or not.

Simulation Environment. The simulation environment created in this thesis effort must perform some basic tasks. The first task is the generation of the actual mission route. This route is planned by the pilot, not autonomously by the computer. This is accomplished using the computer mouse to select waypoints on the map as well as designate which LLTR to select. In order to generate a complete plan, an ingress and egress route are planned for the mission. This process is very simple and requires minimum time. The reason the pilot is required to enter the route is to keep the pilot in the planning process. This not only facilitates a certain degree of personal preferences of the pilot but also serves to brief the pilot as he plans the route. The pilot does not have to spend valuable time acquainting himself with the route. The ability to incorporate personal preferences also creates an environment

in which the pilot is capable of injecting unpredictable facets to the plan. This is actually an important asset of the planning process since a predictable plan will not, in some cases, surprise the enemy and may actually benefit the enemy.

An ECM strategy against a specific threat is required by the simulation in order to combat the threats. This strategy is maintained and generated by the knowledge base. The strategy is an ordered list of ECM techniques to use to combat the threat. The list is ordered based on how effective the technique is against the current situation. For example, the most effective technique is placed towards the front of this list. The generation of the overall ECM strategy to combat all threatening threats is generated using a search. The search is discussed in the following chapter. MU underlies the implementation of the ECM strategy. MU maintains knowledge about the current threat environment and generates the ECM list based on this knowledge.

Creation of the threat environment is a required portion of the simulation. The simulation would be meaningless unless it had a threat environment to reason about. The threat environment is the collection of threats the pilot must consider during his planning process. Implementation of the threat environment is accomplished by

placing threats on the map using the mouse. The information about the threat environment is updated in the knowledge base.

A strike package must be identified by the simulation. This strike package includes the penetrating aircraft in addition to any supporting aircraft. A stand-off jammer may be included in the simulation to help jam threats.

A terrain map must be provided to the pilot during the planning phase. The map is used to select the mission route and can be queried for information such as latitude, longitude, or elevation.

Pilot preferences are a part of the simulation environment that are not addressed in this thesis in great detail. The preferences of the pilot include such things as whether he prefers to completely avoid AAA sites, whether he prefers to try to maneuver his aircraft away from the threat rather than jam it, or whether he prefers an ECM technique over another (e.g. using chaff instead of a jammer). This thesis uses pilot preferences to a certain degree when searching for the optimal ECM strategy. This is discussed in greater detail in the following chapter.

The current Soviet doctrine concerning the application of electronic warfare is a required feature of the simulation. The doctrine includes information such as when to activate a threat or how to reconfigure the threats knowing that some threats may be degraded by jamming or

destruction. This doctrine is currently implemented using the knowledge base. The characteristics of the threats and how the threats may reconfigure are implemented using combining functions in MU.

Modify the Simulation Environment. Due to the dynamic nature of the electronic warfare domain, provisions must be provided to alter or update the simulation environment. These modifications are supported in this thesis and are discussed in this section.

After the pilot plans his initial route, he must have a way to alter the route. Since the simulation provides feedback to the pilot on how effective the ECM strategy generated by the search is, the pilot may decide to alter the mission route. This capability is supported by this thesis. The pilot may move waypoints or add new waypoints using the computer mouse.

As intelligence information about the capabilities of the enemy's threats changes, the recommended ECM techniques to combat the threats may also change. Updating this information is essential in order to generate a truly optimal ECM strategy against all threats. This capability is supported by this thesis and is implemented using a combining function in MU as well as an interface to the user that acquires ECM techniques to use against a given threat.

Another result of changing intelligence information is the requirement to update the threat environment. This is required in order to provide the pilot with the latest intelligence data. Modifying the threat environment is implemented using the mouse to place threats or move threats to any location on the map. This capability also benefits the EW engineer by providing an environment that is easily modified. This allows the engineer to test ideas about how an ECM technique might work against a specific threat configuration.

The ability to change the configuration of the strike package is necessary for a successful planning system. The configuration of the aircraft must be considered during the planning process so the time and fuel constraints can be calculated. For example, the configuration might not include a jammer that is crucial against a certain threat. Changing the configuration of the aircraft to match the actual configuration or the desired configuration is essential and is supported by this thesis using the Stores Management System.

Performing the Simulation. Actually performing the simulation can be accomplished in different ways. This section presents some of these alternatives.

A time-driven simulation is performed by incrementing the simulation in fixed time intervals. For example, the environment is updated every minute. This is the approach

taken for the simulation capability in this thesis. Implementing the time-driven simulation is done by incrementing time by a user-supplied time interval and then updating the simulation objects as appropriate.

The other form of simulation is the event-driven simulation. This form of simulation is characterized by incrementing time based on when an event occurs. For example, since no events occur until the first threat is entered, the simulation could be incremented to the point when the threat is entered. This is not implemented in this thesis.

Regardless of the technique used to advance the simulation, the objects interact with each other. The aircraft is flown along the planned route while applying the suggested ECM. As the threats are jammed, they may notify the other threats that an aircraft is approaching. This allows the network of threats to reconfigure to present the worst case scenario against the aircraft. The implementation of this technique is performed using the knowledge base. As threats are jammed, they can notify other threats by sending messages throughout the knowledge base.

Simulation Features. Several features may be incorporated into the simulation. However, only a few of these features are presented in this section.

The ability to display threats in a manner that conveys the most information to the pilot is a simulation feature that must be addressed. This thesis represents threats by displaying the lethal range of the threat as well as the radar capabilities on the map. Another approach to the threat representation is to display danger indices. These indices would illustrate graphically the levels of danger at each location on the map. For example, the darker regions of the map could represent the more dangerous areas. This allows the pilot to perceive the most lethal areas at a glance. However, this technique is not implemented in this thesis. In order to be robust, the display would have to change as the altitude of the aircraft changes. This represents a computational problem beyond the current capabilities of the Explorer hardware with respect to time.

Terrain masking is the ability to use the terrain of the threat environment to the pilot's advantage. The capabilities of the threats can be degraded due to the terrain. For example, a radar system cannot detect an aircraft behind a mountain. The pilot recognizes this fact and plans his mission with terrain masking in mind. This thesis does not implement terrain masking. However, previous thesis efforts at AFIT as well as current research being conducted at contractor facilities have investigated terrain masking. An example is the route planning aid (RPA) described in the previous chapter.

One of the more important simulation features is the capability to create and view a simulation trace. This trace allows the user to inspect the interactions of the simulation objects. The results of the simulation must be presented to the pilot in a easily readable format. The output of the simulation is saved to a file in the form of a table. This file may be viewed on the screen upon request or printed on a printer for future reference. The output includes the interactions of the simulation objects as well as the times of the interactions.

End game is the stage of a combat in which the threat launches a projectile against the penetrating aircraft. End game includes the phase of the combat that pits the projectile against the aircraft and includes how the threat projectiles react once launched from the threat site. During end game, the primary objective of the pilot is to avoid the projectile at all costs. Projectile end game is not supported in this thesis. Due to the complex aerodynamics of end game simulation, this feature is not implemented. However, if an end game were to occur, the simulation would have to calculate the aerodynamic performance parameters of both the aircraft and the projectile to determine if the launch was a success. This computational complexity is beyond the scope of this thesis. The absence of the end game calculations does not impair the

ability of the simulation to provide meaningful qualitative measures of the effectivity of the ECM strategy.

Probabilistic radar acquisition is the ability of the threats to acquire a radar signature of the aircraft. The probabilistic nature of this feature is implemented in this thesis by determining the most probable mode of the threat given the aircraft route. This feature is required for the simulation in order to reason properly about the effectiveness of the suggested ECM strategy.

Generic terms are used to represent the ECM equipment used in this thesis. The equipment is represented using ECM techniques. In other words, a specific jammer may be capable of a jamming technique called 'ecm-2'. The purpose of this generic designation is twofold. First, this prevents the use of classified data to match specific ECM equipment or techniques against specific threats. Second, this generic designation facilitates future expansions to include classified information. The equipment representation can be broken down to a more detailed level instead of the current top-level representation. For example, power and frequency requirements may be implemented in future versions.

The doctrine of how the threats reconfigure during the simulation is best described by how the enemy will react given a certain ECM technique is applied. This feature is a

necessary element of the simulation. A doctrine is required to dictate the responses of the threats. Consequently, the enemy's doctrine is incorporated into the knowledge base.

Planning Features. Planning features are those features that control how the planning process is implemented. Various planning operations are presented in this section.

An autonomous route planner is one approach to the route selection problem. Allowing the system to plan the mission route given the preferences of the pilot is an feature that is not incorporated. This would allow the pilot to enter his preferences relating to the route planning process and having the computer system generate the route. Since an autonomous approach is not used, the pilot has complete control of the route selection process. Allowing the pilot to control the route selection facilitates a better understanding of the route by the pilot. "Active pilot involvement in tactical mission planning is essential for successful mission accomplishment" (Bahnij, 1985:IV-13).

The planning or scheduling of the ECM techniques to combat the threats is a significant part of this thesis. Based on current data, the most effective ECM strategy to use against a threat environment is derived using a search technique. The specifics of the search are discussed in the following chapter.

Critiquing Features. Critiquing the results of the planner is not the primary focus of this thesis. Most aspects of the critiquing process are beyond the scope of this thesis. However, this section presents some issues relating to this process.

Critiquing the mission route is the ability to reason about the qualitative merits of a mission route. This is not implemented in this thesis. However, a complete critique of the route should include reasoning about the route survivability and how well the route satisfies constraints. A route critique can be a powerful tool for the planning process. After the pilot reviews the results of the critique, he may decide to alter his route to increase the survivability of the mission.

ECM strategies are critiqued by the simulation. The effectiveness of the strategies are determined based on the simulation results. This, in effect, critiques the ECM strategy suggested by the search. This operation is discussed in greater detail in the following section.

Man-Machine Interface. Since the only means of communication between the pilot planning a mission and the planning system is the hardware and software of the system, the hardware and software must be easy to use and provide meaningful and timely data. The pilot must be comfortable with the interface between himself and the computer.

Planning systems are characterized by environments in which the man-machine interface is constantly being evaluated. This section discusses the man-machine interface of the system.

Graphics. One of the quickest and most convenient means of providing information to the pilot is via visual input. Graphics should play a major role in any mission planner. The complexity of the information required for such a task precludes the use of any other medium. Additionally, pilots are more visually oriented than an average human (Bradshaw, 1986:45). This phenomenon dictates the use of graphical information to the pilot.

The foundation for the planning process is a map of the area to be penetrated. This concept is maintained in this thesis. A digitized map of Nellis Air Force Base and its surrounding ranges is used for this mission planner. The selection of the Nellis map was based on the availability of digitized maps. All objects are placed or located on the map.

Threats are represented by a threat designation surrounded by a circle. The threat designation identifies the threat as well as indicates the actual position of the threat. The threat circle represents the lethal range of the threat's projectile. Associated with each threat is a radar. The radar of the threats are represented with a cone to indicate the field of view of the radar. Since an early-

warning radar and a command center provide information to threats about the penetrating aircraft, these two objects are also classified as threats. However, an early-warning radar does not have a projectile; therefore, a circle to represent the lethal range of the projectile is not relevant. Similarly, a command center, not having a radar nor a projectile, will not have a circle nor a cone.

The target is represented by a triangle. The initial point (IP) is represented by a square. All other turnpoints of the route are represented as circles. These objects include the waypoints, home base, and the low-level transit routes (LLTR). The actual legs of the route are displayed as lines between the turnpoints.

A stand-off jammer (SOJ) may be incorporated into the mission. The stand-off jammer is represented as text in the upper right-hand corner of the map in a black rectangle. This representation eliminates the possibility of confusing the SOJ with the penetrating aircraft.

The forward edge of the battle area (FEBA) is represented with a curved line.

The aircraft configuration is represented using the Stores Management System (SMS). The SMS displays the current configuration of the aircraft. The configuration includes the munitions as well as the ECM resources.

Speech Output. The mission planner has the capability to direct the actions of the pilot by verbally telling the pilot what to do next. Also, this facility can be used to warn the pilot of dangerous conditions. However, the speech capability of the planner may be disabled by a press of a button if the pilot prefers a silent machine.

Pilot Input. The man-machine interface also includes inputting information into the planner. The two means of acquiring information from the pilot are by the keyboard or by using the mouse. Since the mouse provides a quick and accurate interface to the mission planner, the mouse is used for the majority of the interface requirements. The keyboard is used in cases where using the mouse is simply not feasible.

Logical Sequence of Planning Options. Presenting awkward or confusing planning options to the pilot may degrade his confidence in the planner. For example, the planner should not allow the pilot to plan his mission route before he loads the air tasking order. The planning options are presented to the pilot in a logical order based on the current phase of the planning process.

Requirements Selection. These requirements are by no means the minimum acceptable for the prototype to be considered a completed product. The researcher selected the more realistic requirements and incorporated them into the prototype. The other requirements are presented to

facilitate a better understanding of how complex a mission planner can be. As previously mentioned, a requirements matrix was developed and is located in Appendix D. This matrix describes the various requirements presented in this section, how they are implemented in this planning system, and what an operational system would require.

The complexity of a software package can sometimes be measured by the number of interfaces required to the user. If a user is required to remember how to interact with the various interfaces, he may become overwhelmed. The software should guide the user through the system with minimum effort by the user. As the previous paragraphs indicate, several interfaces are required in order to provide a realistic environment for mission planning with electronic warfare considerations. However, the interfaces are designed to allow the user the greatest degree of freedom while making the planning process simple.

Tool Selection

Tactical mission planning is characterized by the requirement of working with a map. Generating and displaying a map on the screen of a computer requires a tremendously large memory capability of the system. This capability was one of the limiting factors in the selection of the computer system. The chosen system must be capable

of maintaining large amounts of information while simultaneously possessing computational speed. A computer system that requires long periods of time to derive a solution will generate skepticism from pilots.

Hardware Considerations. These two requirements limit the number of computer system alternatives. First, microcomputers are currently limited to an insufficient memory capabilities. This limitation prevents the implementation of the mission planner on a microcomputer. Second, several minicomputers were available during the development of the mission planner. However, due to the limitation of allocated memory, the minicomputers were deemed unacceptable. The next alternative is to develop the planner on a lisp machine. Since the immediate predecessor of this mission planner was implemented on a Symbolics 3600 series lisp machine (Bradshaw, 1986:38), an obvious choice of a development environment is a lisp machine. This would minimize the coding effort required for rehosting purposes. Another limitation of the development environment is the fact that MU (Managing Uncertainty) was developed on a TI (Texas Instruments) Explorer. The MU software was released to the researcher in load band form. This prevents using the software on other machines other than an Explorer. Since one of the primary objectives of this thesis was to perform a technical evaluation of MU, this limitation was

not negotiable. Therefore, the TI Explorer was chosen as the development environment for the mission planner.

Several assets of the Explorer system support this selection. The Zmacs editor of the Explorer system proved to be a powerful software development tool. The incremental compilation capability of the editor provided an excellent facility for rapid modifications of source code. This facility provided a means of compiling only the regions of code that had been changed instead of compiling entire buffers or files to update the system after modifications. The editor of the Explorer is not the only asset considered during the tool selection.

Another feature of the Explorer that was considered during tool selection is the ability to create a system. A system is used to automatically maintain the proper file structure for the mission planner. The system facility also proved to be extremely powerful during program development. Upon request, the Explorer, using the system facility, would automatically compile and load all necessary files in the proper order for the mission planner. Additionally, the system facility could be used by the editor. The editor uses the system facility to read into buffers all files required for the mission planner. This provides quick and easy access to all germane files. String searches are also supported over all files (not just one file) using this feature.

A host of other facilities exist within the Explorer system. Rather than dwell on all of these facilities, the final facility is presented. The graphics capabilities of this system provided a rich environment in which to develop the mission planner. The graphics capabilities include the ability to place any object (picture) anywhere within a window. This was extremely significant for the development of the map. Also, the graphics editor was very useful for generating graphical images required for the planner.

All of the previously mentioned reasons lead to the selection of the TI Explorer as the development hardware for this thesis. The Explorer is a standard delivery system with three 112 megabyte (formatted) disk drives, one 1/4 inch tape cartridge drive, a WD900 disk drive with a storage capacity of 512 megabytes (formatted), and 8 megabytes of physical memory. This created a system configuration of 212 megabytes of virtual memory.

Software Considerations. The development software used in this thesis includes Explorer system software version 2.78, Zetalisp, the Flavors package, and finally version 3 of MU. The following paragraphs describe each package and why they are required.

The Explorer system software controls the Explorer system and is obviously required for the operation of the system.

Zetalisp is a dialect of the lisp language and is used in the thesis as the primary programming language. The selection of Zetalisp is based on the implementation of the TMP developed by Bradshaw. The TMP was implemented using Zetalisp. Also, since lisp is an interactive language, functions and ideas can be tested instantaneously using a lisp listener. This facilitates quick program debugging as well as an easy mean to probe a program that contains errors. After the program halts, the computer maintains the state of the program. Therefore, the state can be queried to determine the cause of the fault. To prevent a modification effort of existing software, Zetalisp was adopted.

The same reasons hold for the selection of the Flavors package. Since Bradshaw's planner used Flavors to represent objects, the Flavors package was also used in this thesis. Abandoning the Flavors representation of various objects would have entailed unnecessary and major modifications to the software.

MU Selection. Finally, MU was used in this thesis for two reasons. First, a technical evaluation of MU is a primary objective of this thesis. Second, MU exhibited characteristics that seem to show it to be an excellent tool for the problem.

MU is a frame-based representation language that provides powerful tools for building inference networks (Cohen et al., 1987b:5). MU provides a frame editor useful for creating of altering items within frames. KEE (Knowledge Engineering Environment) underlies MU. That is to say MU is built using the abilities of KEE to develop a powerful reasoning tool. Frames are represented in MU much the same way as KEE. Inheritance plays a significant role in the development of MU knowledge bases. Similar to KEE, objects may inherit characteristics of a parent. This proved to be a valuable asset of MU.

MU's representation of knowledge centers around the concept known as features (Cohen et al., 1987b:7). Features are the foundation of MU; planning decisions are made from the information contained in features and their associated values (Cohen et al., 1987b:7). The nodes of the inference network may have several features associated with them.

Four classes of MU features are currently supported. The first feature is the static feature and its value is specified before run time and does not change after the planning process begins. The datum feature's value is acquired from the user at run time. The value of the dynamic feature is derived from values of other features by a combining function. The fourth feature is a focus feature. A user-defined predicate is used to derive the value of a focus feature (Cohen et al., 1987b:8).

One of the more powerful properties of MU is the combining function. Combining functions derive the values of dynamic features and consequently maintain a current inference network. This is accomplished by propagating values throughout the inference network. The combining function updates the value of the dynamic feature whenever new information becomes available as a result of querying the user or propagation of a new value. Combining functions currently resemble rules.

"MU is a development environment for knowledge systems that reason with incomplete knowledge" (Cohen et al., 1987b:2). As discussed in the previous chapter, the domain of electronic warfare is complicated with incomplete knowledge in several areas. For example, the intelligence information the pilot uses during his planning process may contain incomplete information about the threat environment. This aspect of MU makes the tool promising for this application.

MU is an environment for building prospective reasoning systems (Cohen et al., 1987b:1). "Prospective reasoning is a form of planning in which knowledge of the state of the world and the effects of actions is incomplete" (Cohen et al., 1987b:1). In different words, this form of reasoning "involves answering the question 'What shall I do next,' given uncertainty about the state of the world" (Cohen et al., 1987b:14). The domain of EW fits nicely into the realm

of prospective reasoning. First, as previously mentioned, not all information about the threat environment is complete. Second, the effects of applying an ECM technique against a threat are not completely known during the planning process. Third, how the threats reconfigure to combat the penetrating aircraft is not completely known. The threats, in effect, work on the question "What shall I (we) do next given what we know and how confident we are with the information." These examples provide stronger support for the use of MU.

MU does not incorporate a planner within the inference network. Instead, a planner must be built to exercise the network. However, MU does provide "tools for building planners and incorporating expert problem-solving strategies within them" (Cohen et al., 1987b:6). Figure 2 illustrates the interactions and functions of MU and the planner.

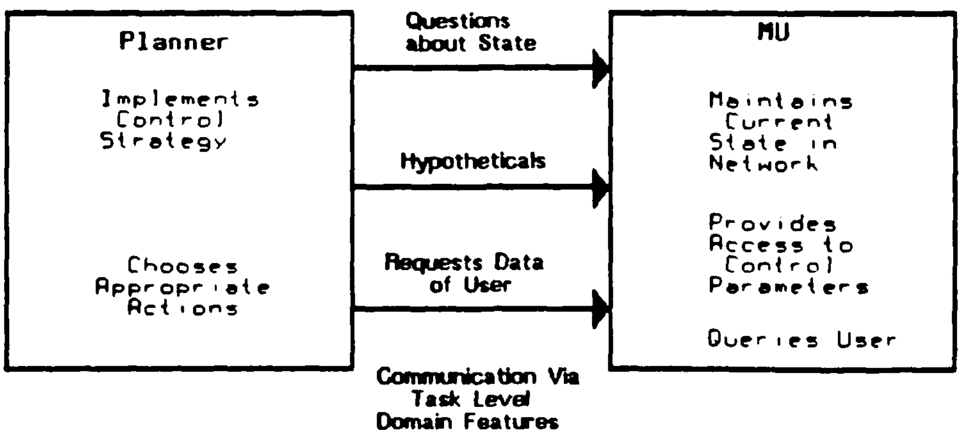


Figure 2. MU System Schematic
Source: (Cohen et al., 1987b:8)

MU promises to be a powerful tool for the creation of a sufficiently robust inference network for this thesis. Also, features and combining functions seem to provide convenient means of representing the properties of the objects of the EW domain. For example, all characteristics of aircraft and threats can be represented using MU's features. The ability of the objects to interact with each other can be represented using combining functions. Therefore, MU was determined to be the right tool for this thesis.

Summary

This chapter has discussed the considerations required by a system designer in order to produce a usable and acceptable ground-based tactical mission planning system. Additionally, the desired requirements for a prototype tactical mission planner were presented. Finally, the tool selection process was discussed to find the correct tools for the development of the planner.

The top-level integration of the four explored ideas is also presented in this chapter. The interactive planner provides a rich mission planning environment for the user. The constraint-directed search finds a plausible ECM strategy to combat the threat environment. The knowledge-based simulation determines the effectiveness of the ECM strategy by reasoning about the uncertainty of the domain.

Figure 3 illustrates the top-level integration.

The following chapter, chapter IV, will describe the detailed design of this integration used to develop the tactical mission planning system. The detailed design is based on the conceptual design presented in this chapter.

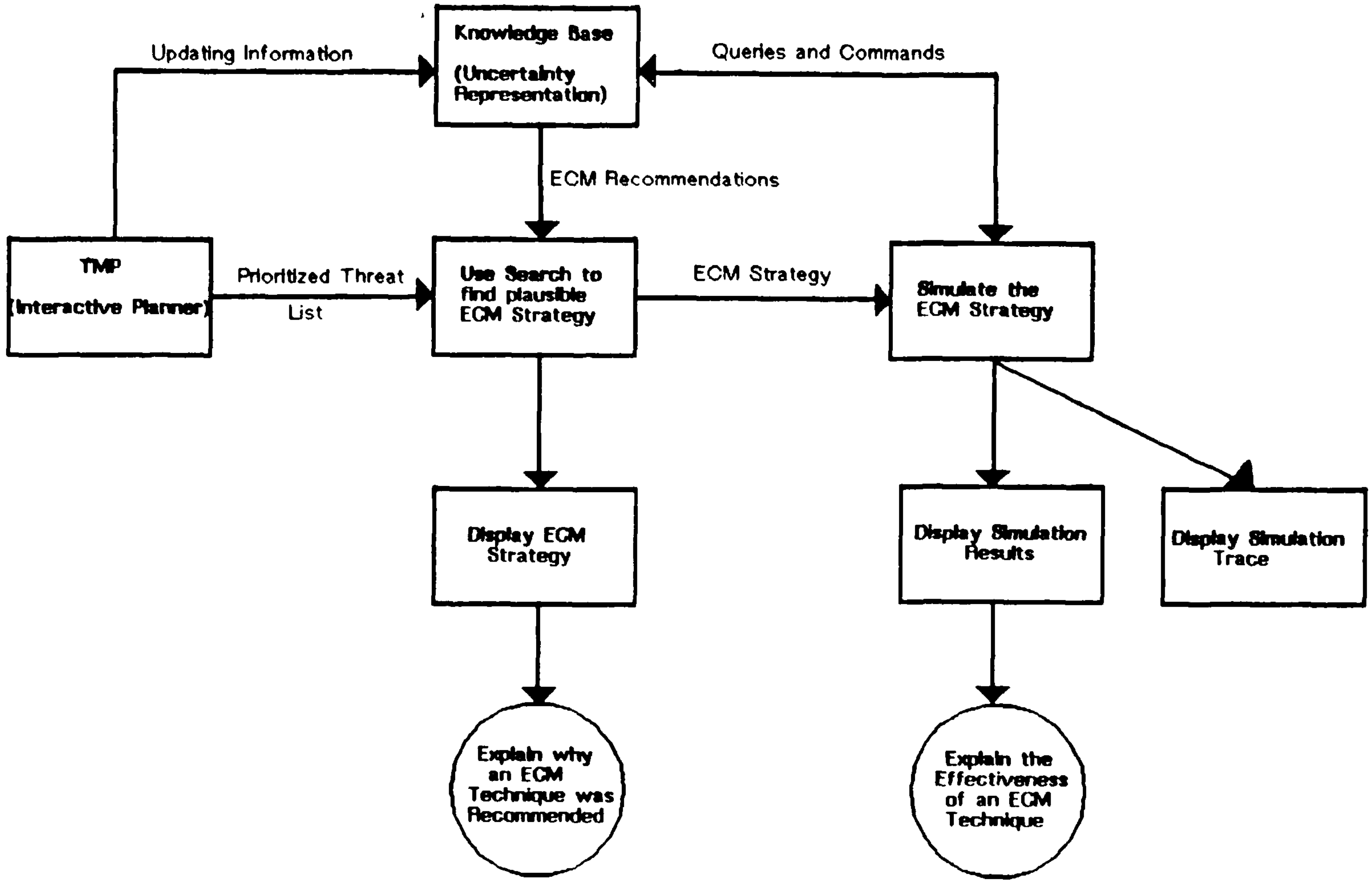


Figure 3. Top-Level Integration

IV. Detailed Design

Chapter III discussed the desired system specifications and the tool selection for an interactive mission planner and simulation for an attack type Offensive Counter Air (OCA) mission. These specifications were used to complete a detailed design of the tactical mission planner. This detailed design is presented in this chapter.

The simulation can be broken into four areas. First, a search for the most effective ECM strategy against the threat environment must be performed. Second, the search results must be presented to the user thereby providing the user with the capability to question the reason why a specific ECM technique was proposed. Third, the simulation must be performed to determine the effectiveness of the suggested ECM strategy. Finally, the results of the simulation must be presented to the user. This provides a facility for the user to have the effectiveness explained. Figure 3 illustrates these four components and how they interact. Each area is discussed in detail in this chapter.

ECM Strategy Generation.

The researcher knows of no algorithm currently available for the generation of an ECM strategy to combat a threat environment for a given mission. Additionally,

experts capable of assigning the ECM strategy do not exist. This prompted the creation of an ECM assignment algorithm or technique.

The driving factor of the selection of the assignment algorithm is current knowledge of the assignment task. Four elements of knowledge are currently known about this task. These facts are used to select an ECM assignment algorithm and are presented in the following paragraphs.

First, the lethality of the threats and the order in which the threats are processed must influence the selection. The priority of the threats must be considered during the ECM assignment. This would allow the user of the algorithm to prioritize the processing of the threats based on his perception of threat lethality.

The second controlling factor in the selection of an ECM assignment algorithm is the amount and types of ECM resources available during the assignment process. The algorithm must be able to handle various ECM techniques.

The next element of knowledge currently known is the preference of which ECM techniques to apply to a threat given the current state of the threat environment and the penetrating aircraft.

The fourth and final element concerns the satisfaction of constraints. The aircraft is only capable of carrying a limited number of ECM resources. These resources include a limited number of expendables in addition to a limited

number of jammers. The jammers are further constrained by the limited power capabilities of the aircraft. Also, some jammers are limited to jamming one threat at a time. All of these constraints must be satisfied during the creation of an ECM strategy to combat effectively the threat environment. A popular technique to solve constraint satisfaction problems is search (Rich, 1983:94).

As mentioned earlier, the threat environment includes numerous threats. Due to the vast number of threats the penetrating aircraft must consider, the ECM assignment algorithm must be capable of handling numerous decisions. Avoiding a combinatorial explosion is a major consideration in the selection of an algorithm. The requirement to handle numerous decisions coupled with the four elements presented in the preceding paragraphs, point to implementing a weak problem-solving technique -- search.

The ECM assignment algorithm is implemented using a search. To prevent the possible combinatorial explosion of the search, the constraints of the domain, e.g. limited resources, are exploited to simplify the search.

Constraint-Directed Search

In order to present the pilot with the best possible ECM strategy for a given route and threat environment, a constraint-directed search is performed. The search is considered a constraint-directed because of the exploitation

of the constraints in this domain (EW) to simplify the search. The search also addresses the four elements discussed earlier.

State Representation. The state representation of the search includes the following information: a list of threats that need to be processed including the time period the threats are considered a threat to the aircraft and the most probable mode of the threat (surveillance, acquisition, track, or missile-launch), currently scheduled ECM against threats, ECM that is available to combat threats later in the search, and a list of processed threats along with the ECM applied to the threat. Time is metered with respect to simulation ticks. For example, a time of 35 represents simulation tick number 35. To clarify this representation, the initial or root node of the search is illustrated in Figure 4.

```
(((threat-1 20 30 missile-launch)
  (threat-2 25 60 track)
  (threat-3 70 100 acq))

nil

((ecm-1) (ecm-2) (ecm-3) (ecm-4)
 (chaff 4) (flare 4) (decoy 4))

nil).
```

Figure 4. Search Root Node

In a effort to keep this thesis unclassified, generic ECM techniques (e.g. ecm-1) are used.

The first list of the root node represents the threats that are considered a threat to the aircraft. These threats and the associated times are identified by performing a intelligence-gathering mission/simulation. This simulation advances the aircraft along the planned route simply to identify the threats the aircraft enters. In other words, the simulation records which threats the route crosses. A crossing occurs if the aircraft enters the radar coverage of the threat. Therefore, this simulation does not consider the uncertainty of the information it is gathering. It assumes all information to be certain. For example, threat locations are assumed certain. The implications of assuming the information to be certain is discussed in the section of this chapter titled "Simulation". As the aircraft encounters a threat, the threat and the time are recorded. As the aircraft continues penetrating the threat, the closest point from the center of the threat to the route is calculated and stored in the MU knowledge base along with the aircraft above ground level (AGL). These values are used by MU in determining the most probable mode of the threat. Finally, as the aircraft exits the threat, the exiting time is recorded. After the intelligence-gathering simulation is completed, a list of threats is stored in the global variable *threats-crossed* along with the mentioned information. This variable is used by the search to create the root node.

Since the root node represents the state before any ECM is applied, the scheduled-ECM list is nil (empty) as well as the processed threats. The ECM available for use contains all ECM resources of the aircraft since there are no ECM techniques currently scheduled against threats. The available ECM in Figure 4 represents four ECM jamming techniques and three forms of expendables: chaff, flare, and decoy. All three expendables have four units (e.g. four flares). The root node is yet one example of the state representation. To facilitate a better understanding of this representation, another node is presented in Figure 5 and discussed. This node is representative of a partially completed solution since all threats are not combated by an ECM technique (e.g. threat-3).

```
(((threat-3 70 100 acq))

((ecm-4 25 60) (chaff 20 30))

((ecm-1) (ecm-2) (ecm-3) (ecm-4)
 (chaff 3) (flare 4) (decoy 4))

(((threat-2 25 60 track) (ecm-4 25 60))
 ((threat-1 20 30 missile-launch)  (chaff 20 30))))
```

Figure 5. Partial Search Solution Node

This node has one threat, threat-3, that needs to be processed before the search terminates. The scheduled ECM is apply ECM jamming technique ecm-4 from tick number 25 to tick number 60 and deploy chaff at 20 ticks. The available ECM depicts the resources available after the scheduled ECM

is applied and is maintained current for any given node. In other words, the ECM constraints are monitored to insure constraint violates are detected and that node eliminated from the search. The processed threats include threat-1 and threat-2. The associated ECM to combat these two threats is also represented. This final list, the processed threats list, is used to display the search results to the user after the search finds a goal node. The following section discusses how a goal node is detected and how the search execution progresses to find this node.

Search Implementation. As previously mentioned, the search technique is a constraint-directed search. However, the underlying control strategy for the search is hill-climbing. Hill-climbing was selected for this application because of the lack of global knowledge of the domain. That is, heuristic evaluation functions concerning how far the search is from a goal node or the cost of a partial path could not be determined during the search. This leaves only the local constraints of the domain (e.g. knowledge about which ECM technique is most effective against a threat) to simplify the search. Hill-climbing uses these constraints to determine the optimal path to traverse. The constraints determine how far the search progresses for any path. If a constraint is violated on a path, the remainder of that path is not considered in future search operations. One approach to the constraint satisfaction problem is to develop a

unimodal hill-climbing search (Rich, 1983:95). A unimodal hill-climbing search does not consider local maxima other than the goal nodes. This form of search is implemented in this thesis and is referred to as a constraint-directed search.

The goal node for the search is when the list containing the threats to be processed of a node is empty or nil. This indicates that all threats have been processed and have an ECM technique scheduled. The search must completely traverse a path of the search tree to find a goal node. It is important to note that the depth of the search is always limited to the number of threats that require searching. For example, if a search must find ECM techniques to combat 15 threats, the depth of the search will be 15. Therefore, if all ECM techniques are available at required times, the search will follow the left-most path down 15 levels until the last threat is processed. The list containing the processed threats along with the ECM applied is formatted and displayed after a goal node is found.

The search uses a queue to hold partial paths. Partial paths are generated by expanding the current node. An expand function is used. This function expands the partial path at the front of the queue such that the path will contain all children (suggested ECM techniques) of the path. The characteristic that distinguishes this form of search from others is the requirement to sort the children at the

front of the queue. The suggested ECM techniques are supplied by the MU knowledge base upon request. MU considers the effective altitude of the threat, the AGL of the aircraft at the closest point, and the probable radar mode of the threat in determining the most effective ECM strategy list. This list is supplied to the search already in sorted order by MU. In other words, the suggested ECM techniques are already in the order that is consider most effective. For example, if the most effective ECM for a threat is ecm-2 and the next most effective is ecm-4 and the next most effective is chaff, then the list would be (ecm-2 ecm-4 chaff). This alleviates the requirement that the search must sort the children of the node before expanding it; the list is already sorted. This also insures that the most effective techniques are searched first.

If the search reaches a point where a constraint is violated, the associated branch and all of its children are pruned from the search by not expanding the violated branch. This pruning process is performed by a function call 'check-constraints'. This insures the violated constraint is not addressed later in the search by one of the children. Another benefit of the pruning of violated constraints is the increase in search speed. Since an exhaustive search of the tree is not required (some of the branches have been pruned from the tree), the search will not have to waste time exploring unproductive branches.

The general approach to the search is first determine/ create the root node. The next step is to create a queue in which partial paths will be maintained. The only partial path at the beginning of the search is the root node. Select the first partial path from the queue. Since children are always sorted, the first partial path always contains the most optimal ECM techniques for the threats. Select the first threat from the front of the 'threats to be processed' list of the partial path. This threat is used to expand the partial path by asking the knowledge base to supply a sorted list of effective ECM techniques against this threat. The knowledge base, using current knowledge about the threats capabilities and the threat environment, generates this list and passes it to the search. An example of a sorted list is (ecm-3 ecm-2 chaff). This list indicates that the most effective ECM technique to use against the threat in question is ecm-3. If ecm-3 is not available, ecm-2 should be used and so on. After the search receives this list, it checks for constraint violations for each ECM technique in the list. If a constraint violation is detected while checking a technique, that ECM technique is removed from the list. This prevents constraint violations in the search and effectively prunes away unproductive paths since this path will not be expanded. Once the valid (no constraint violations) ECM techniques are determined, the partial path at the front of the queue is

expanded to include the new techniques. This is accomplished by appending the new nodes formed by the valid ECM techniques to the front of the partial path. This can and usually does create multiple new partial paths. These new partial paths are appended to the front of the queue in place of the original partial path. This same process is applied to the front of the queue repetitively until a goal node is found.

However, due to the potential for several threats, not enough ECM resources may be available to combat all threats which means a goal node is never found. This mandates a two-pass search. The first pass performs the search as described. If a goal node is found, the results are displayed. However, if a goal node is not found, a second pass is performed. This second pass is performed exactly like the first pass with one exception. If a threat does not have a recommended ECM technique after constraints are checked (i.e. all ECM techniques violate a constraint), no technique is used and none is the suggested ECM technique against the threat. This insures that an ECM strategy will always be generated by the search instead of having the search respond with no goal node found.

Selecting the Threat Processing Priority. The search processes the threats in the 'threats to be processed' list in order of occurrence. In other words, the threats in *threats-crossed* are searched and expanded from left to

right. For example, if *threats-crossed* is ((threat-1 20 30 missile-launch) (threat-2 25 60 track) (threat-3 70 100 acq)), then threat-1 is processed first, threat-2 second, and threat-3 third. The order in which the threats are processed affects the significance placed on the threat. Threats toward the front of *threats-crossed* will have a better probability of commanding the most effective ECM for itself. The remaining threats in *threats-crossed* must now abide by this constraint. For example, if ecm-2 is assigned to combat threat-1, the first threat in the list, the other threats cannot use this technique due to the characteristics of the technique (it can only be applied against one threat at a time). However, effectively combatting threat-3 may be critical to the success of the mission and ecm-2 is the only effective technique. This illustrate the importance of allowing the pilot the flexibility to select his preference for a threat processing priority.

If insignificant or low-priority threats are at the front of *threats-crossed*, then these threats may tie up the ECM resources such that more lethal threats found later in *threats-crossed* will not have sufficiently effective ECM resources. For example, if several threats are in acquisition mode and are found early in *threats-crossed*, they may tie up a jammer needed for a threat that is in missile-launch (considered more lethal than acquisition) and is found later in *threats-crossed*. The pilot requires

means in which to order the list of threats (*threats-crossed*) such that his preferences are addressed.

The pilot may select how he prefers the ordering of the threats in *threats-crossed*. Six ordering schemes are currently available to the pilot. The first scheme allows the pilot to order the list based on the probable mode of the threat. Since missile-launch is considered the most lethal of the modes, all threats that are projected to be in missile-launch are placed at the front of the list. This insures the missile-launch threats have top priority in the planning process. The remainder of the list is completed by the same process. After all missile-launch threats, all tracking threats are added. After all tracking threats, all acquisition threats are added. Similarly, surveillance, jammed, and down threats are added.

The second and third ordering schemes use time as the ordering factor. The second scheme orders the threats based on when the threats are entered. For example, the front of the list will contain the threats that are encountered first during the mission. The third scheme orders the threats based on the order in which the aircraft exits the threats. For example, the front of the list will contain the threats exited first. This may sound identical to the second scheme, however, due to the varying ranges of threats, the order of entrance is not always the same as the order of exit.

The fourth and fifth schemes consider the type of the threats. Scheme four places all SAMs toward the front of the list before any other threats then AAAs and finally radars. This scheme also performs an ordering on the mode of the threats. For example, the list ((sam-1 20 30 track) (aaa-1 30 40 acq) (sam-2 25 60 missile-launch) (aaa-2 10 60 track)) would become ((sam-2 25 60 missile-launch) (sam-1 20 30 track) (aaa-2 10 60 track) (aaa-1 30 40 acq)). This is valuable if the pilot is most concerned with effectively combatting SAM threats. Scheme five is the same as scheme four except AAAs are placed toward the front of the list followed by SAMs and then radars. Once again, the mode of the threats are considered in the ordered of similar threat types.

The sixth scheme orders the threats based on their distance from the target. Threats that are closest to the target are at the front of the list and vice versa.

Displaying Search Results

The search would be worthless unless the results are display to the user. Additionally, the results must be in an easily readable form so the pilot does not spend valuable time trying to locate information thereby causing his situational awareness to decrease. Another rationale for displaying the results is to allow the pilot to query the reasons for a particular ECM selection.

Form of Results. The results of the search are displayed to the pilot in the form of a table. Figure 6 illustrates how the search results are presented to the pilot. The table contains ten elements of information. The first element is the ordering scheme used for the search. The remaining elements pertain to the list of threats. The following information is displayed for each threat: a reference number, the threat encountered, the time the aircraft will enter threat, the time the aircraft will exit the threat, an indication of whether the aircraft is within range of the effective altitude of the threat, the suggested ECM for the threat, the recommended time to start applying the ECM, the recommended time to stop applying the ECM, and finally the sorted list of techniques supplied by the knowledge base. Of course, the stop time is only applicable to the jammers. The expendables only have a time of ejection. However, the expendables do have a life span. This life span is assumed to be equivalent to the period of time required to jam the threat. Therefore, the start and stop times for the table have meaning for all forms of ECM.

Since the number of threats to be combated could be larger than the number of lines on the table, the search-results window is scrollable. If a threat is not presently seen within the window, the top or bottom margin will say either "More Above" or "More Below" respectively. If this

TOP

RECOMMENDED ECM STRATEGY

Using radar-mode search priority.

#	THREAT	ENTER	EXIT	MODE	RANGE	ECM APPLIED	START	STOP	ORDER
1	ew-2	21	112	missile-launch	in	chaff	21	112	(chaff decoy ecm-4)
2	sam-4-site-1	43	92	missile-launch	below	flare	43	92	(flare ecm-4)
3	sam-6-site-2	79	93	track	in	ecm-3	79	93	(ecm-3 chaff decoy)
4	sam-6-site-1	31	48	acq	in	ecm-2	31	48	(ecm-2 ecm-3)
5	sam-11-site-2	38	42	acq	in	ecm-3	38	42	(ecm-2 ecm-3)
6	sam-11-site-1	84	88	acq	in	ecm-2	84	88	(ecm-2 ecm-3)

Search Window

BOTTOM

Search Operations ☐ Change Search Priority ☐ Change Threat ECM Order ☐ Change Screen ☐

Figure 6. Search Results

does occur, the mouse is used to bring the threat in question within sight. The specifics of how to perform this operation is discussed in Appendix B, The User's Manual. The scrolling capability of this window provides quick and easy access to all information.

Since the ECM strategy is displayed in table form, information is easy to digest and locate. The various search priority schemes are easily identified by simply viewing the table. The recommended ECM and the associated times are located on the same lines.

Explanation Capability. An explanation facility is implemented into the search to allow the pilot to query the reasoning process. This facility explains why a certain ECM technique is suggested against a specific threat. This is extremely important in winning the confidence of the pilot. The pilot may be reluctant to blindly use a strategy generated by a search unless he has the capability to verify the reasons behind the selection. This explanation facility provides a window into the reasoning process of the search. The pilot can peer into the window to better understand the reasons behind a suggestion.

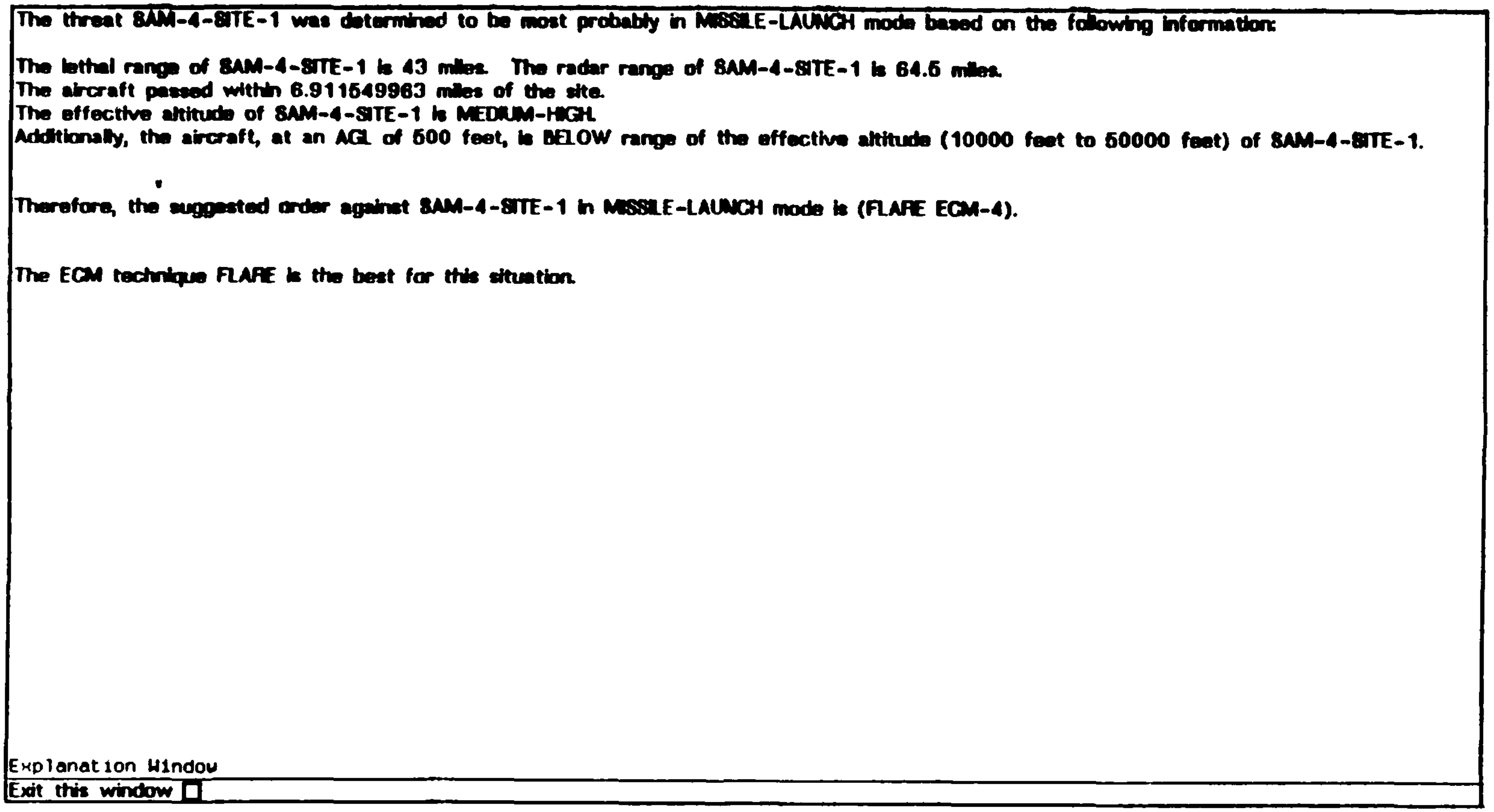
The execution of the explanation facility is implemented by allowing the pilot to select a specific ECM technique that was recommended by the search. This is accomplished by mouse-sensitive lines in the search window. Each numbered line in the window is mouse-sensitive. That is to say that if the mouse is placed on one of these lines, the line will become boxed-in. While the line is boxed, a left click on the mouse will generate an explanation of why the ECM on that line is suggested against the threat on that line. This starts the explanation process. The actual explanation is displayed to the pilot using a window that overlaps the search window. Once again, the specifics of how to operate the explanation facility is provided in Appendix B.

The actual explanation text is generated upon request instead of maintaining this information in each node of the search. This implementation was chosen for two reasons. The first reason deals with the execution speed of the search. Maintaining the information in each node may slow the search considerably by requiring more overhead that may not be necessary.

The second reason for this implementation is explanations may not be required for all searches. Instead of generating this information in the search and then perhaps not use it, the information is generated upon a request from the pilot. This reduces the time required to complete the search while simultaneously providing the necessary information.

Since the search is a constraint-directed search and the priority scheme is known, recreation of violated constraints is sufficient for an explanation. A backward constraint verification is performed on the table. The table is represented within the computer by the list *search-solution*. This list contains all the information required to generate an explanation. For example, the pilot may ask why ecm-3 is recommended to combat sam-11-site-2 knowing that ecm-3 may not be the most effective ECM to use against this threat. The explanation would respond with a message similar to the one in Figure 7. The violated constraints are gleaned from the table. Starting at the ECM

technique in question, the explanation facility proceeds to the front of the *search-solution* list (or to the top of the table) checking ECM techniques as it progresses. Each ECM technique preferred over the suggested technique is checked against the suggested ECM techniques of threats higher in the table. If a match is found, the time of the technique in question and the time of the matched technique are compared. If a time violation is discovered (i.e. the two time period overlap), the appropriate message is displayed. For example, using the previous example, ecm-1 and ecm-3 are preferred over ecm-2. Therefore, an explanation of why ecm-2 is suggested for threat-5 would include traversing the list looking for ecm-1 and ecm-3. When these techniques are located and the applied times for ecm-1 and ecm-3 violate the time period for ecm-2, the reason for suggesting ecm-2 is also found. The ECM technique, ecm-2, is suggested because threats with higher priority need the first two preferences of threat-5. The section in this chapter titled "Selecting the Threat Processing Priority" discusses how to alter the processing priority of the threats if the explanation is not acceptable to the pilot.



The threat SAM-4-SITE-1 was determined to be most probably in MISSILE-LAUNCH mode based on the following information:

The lethal range of SAM-4-SITE-1 is 43 miles. The radar range of SAM-4-SITE-1 is 64.5 miles.
The aircraft passed within 6.911549963 miles of the site.
The effective altitude of SAM-4-SITE-1 is MEDIUM-HIGH.
Additionally, the aircraft, at an AGL of 500 feet, is BELOW range of the effective altitude (10000 feet to 50000 feet) of SAM-4-SITE-1.

Therefore, the suggested order against SAM-4-SITE-1 in MISSILE-LAUNCH mode is (FLARE ECM-4).

The ECM technique FLARE is the best for this situation.

Explanation Window
Exit this window

Figure 7. A Search Explanation

Simulation

The purpose of the simulation is to test the true effectiveness of the suggested ECM strategy. The effectiveness of the ECM techniques is determined by actually flying the aircraft along the mission route and allowing the simulation objects to interact with each other.

Reasoning About Uncertainty. The simulation reasons about the uncertainty of the threat environment to determine the effectiveness of all suggested ECM techniques generated by the search. Since the constraint-direct search did not consider the uncertainty associated with the threats, the suggested ECM strategy was generated assuming all information to be certain. However, this is rarely true and is the reason for a simulation. The knowledge base is the driving factor in the simulation. All knowledge about the domain is stored in the knowledge base. The uncertainty associated with the knowledge is also found in the knowledge base. MU represents uncertainty using qualitative measures of uncertainty, instead of a numeric calculation. This form of uncertainty is used in the effectiveness evaluation. The values that may represent uncertainty are very-uncertain, uncertain, certain, and very-certain. Also, the effectiveness is represented in the same manner and may be one of completely-ineffective, very-ineffective, ineffective, effective, very-effective, or completely-effective.

One of the sources of uncertainty in the simulation is the intelligence information (INTEL). If the information is old, the uncertainty of the actual capabilities of the enemy will be more uncertain. Additionally, if the weather during the gathering of the intelligence information is cloudy, the information will be more uncertain. This tends to increase the uncertainty of the INTEL. Consequently, the uncertainty of the INTEL will affect the effectiveness of the ECM strategy. If the INTEL is very uncertain, the effectiveness of the strategy will be degraded since the strategy was generated using the latest INTEL and assuming the information to be true.

Another cause of uncertainty in the simulation is the terrain of enemy areas. The terrain can affect the capabilities of mobile threats. For example, if the terrain is very rough, mobile threats are more likely to remain in a given location for a longer period of time. This tends to decrease the uncertainty of the INTEL. Therefore, the INTEL is more likely to be correct as to the location of the threats. Conversely, flat terrain facilitates moving threats around and tends to increase the uncertainty of the simulation. This source of uncertainty affects the effectiveness of the applied ECM.

The INTEL age, the terrain, and the weather can be changed using the "Change Simulation Parameters" option of the map. The menu used to change these values is illustrated in Figure 8.

Simulation Parameters	
Enable graphics:	**Yes** No
Ticks per minute:	2
Radar power:	1.5
Surv radar FOV:	30
Acq radar FOV:	20
Track radar FOV:	5
Missile launch radar FOV:	5
Missile launch perimeter:	0.6
Track perimeter:	0.9
Intel age:	4
Environment terrain:	FLAT
Environment weather:	SUNNY
Notify threat number:	2
Do it ☐	Abort ☐

Figure 8. Simulation Parameters

The next element that can affect the effectiveness of the applied ECM is whether the threat was warned by another threat of the approaching aircraft. If a threat was warned, the effectiveness of the ECM will be degraded since the threat will have a high probability of locating the aircraft. This implies that the threat has a longer time span to prepare any ECCM capabilities to defeat the ECM applied.

The ECCM capabilities of the threats is another source of uncertainty. If a threat has an ECCM capability that is capable of defeating the applied ECM, the effectiveness of the ECM will be degraded. Consequently, the uncertainty of the ECM is greater.

Performing the Simulation. The actual simulation advances the aircraft along the route in simulation time increments. The time increment may be changed to vary the granularity of the simulation. For example, the default simulation increment (tick) is 30 seconds. This can be altered to increase the granularity to 10 seconds for each tick. As the aircraft navigates the route the suggested ECM strategy generated by the search is applied. Therefore, as the aircraft enters what it believes to be a threat area (based on the intelligence information), the simulation activates the suggested ECM technique. The effectiveness of the applied ECM is determined by how mobile threat is, the terrain of the threat environment, the uncertainty of the INTEL, the ECCM capabilities of the threat, and whether or not the threat received advanced data about the aircraft from other threats. This information is stored in the knowledge base using features and combining functions.

The threats communicate with each other by a command center (CC). This is how threats warn other threats that the aircraft is approaching. For example, if a threat wants to pass coordinates to another threat, the data must flow

through the CC. This places a great deal of significance on the CC since its destruction or jamming would prevent effective threat communications. For the purposes of the simulation, only a stand-off jammer (SOJ) has the capability to jam the CC. Therefore, when the SOJ is present in the simulation, the CC is considered inoperable and threats cannot pass data between themselves.

The information that is passed from one threat to another is the location of the aircraft. Of course the threat must first know that the aircraft is within its radar. This brings up the question of how does a threat know the aircraft is within range. If the ECM techniques are successful, the threat may never know the aircraft is present. The effectiveness of the ECM is used as a measure of whether the threat "sees" the aircraft. An ineffective ECM technique means the aircraft was spotted and possibly fired upon. An effective ECM technique suggests the aircraft completely confused the threat such that it penetrated without being detected. Of course there are more possibilities other than being fired upon and eluding the threat. Perhaps the threat found the aircraft but was unable to fire on it. In this case the threat would send the information it acquired to the CC. The CC would in turn send a warning to other threats. Once again, this is implemented using features and combining functions in MU.

The simulation proceeds in the following manner. The aircraft is moved along the route at each simulation tick. The suggested ECM techniques are applied to the threats. As ECM is applied, the effectiveness of the ECM is determined using the information discussed earlier. If the ECM is truly effective (very-effective), the aircraft is undetected and no actions are taken by the threat. However, if the ECM is anything less than very-effective, the threat detects the aircraft and sends a warning to the CC. If the CC is operable (SOJ not in simulation and a CC is present in the simulation), the information is sent to the following threats on the route. The number of threats the CC is capable of notifying at one time is selectable using the "Change Simulation Parameters" option of the map (See Figure 8). The default is two. The reason for using only the next two is because the significance of the information will be degraded after a time period. The aircraft could change direction for example. After the aircraft completes the route, the evaluation information is displayed to the pilot.

Presenting Simulation Results

As mentioned earlier, the simulation stores information about the effectiveness of the ECM strategy in MU. The effectiveness of the suggested ECM strategy is one of the desired outputs from the simulation. The other desirable output is a trace of the simulation. All information

required for the results output is easily accessible in MU. The output of the simulation results is a table of the effectivity of the ECM strategy. The table contains information such as the threat penetrated, the mode of the threat, the ECM technique applied against the threat, and the degree to which the ECM effective against the threat. This information is presented to the pilot in table form for easy readability. Figure 9 is an example of simulation results.

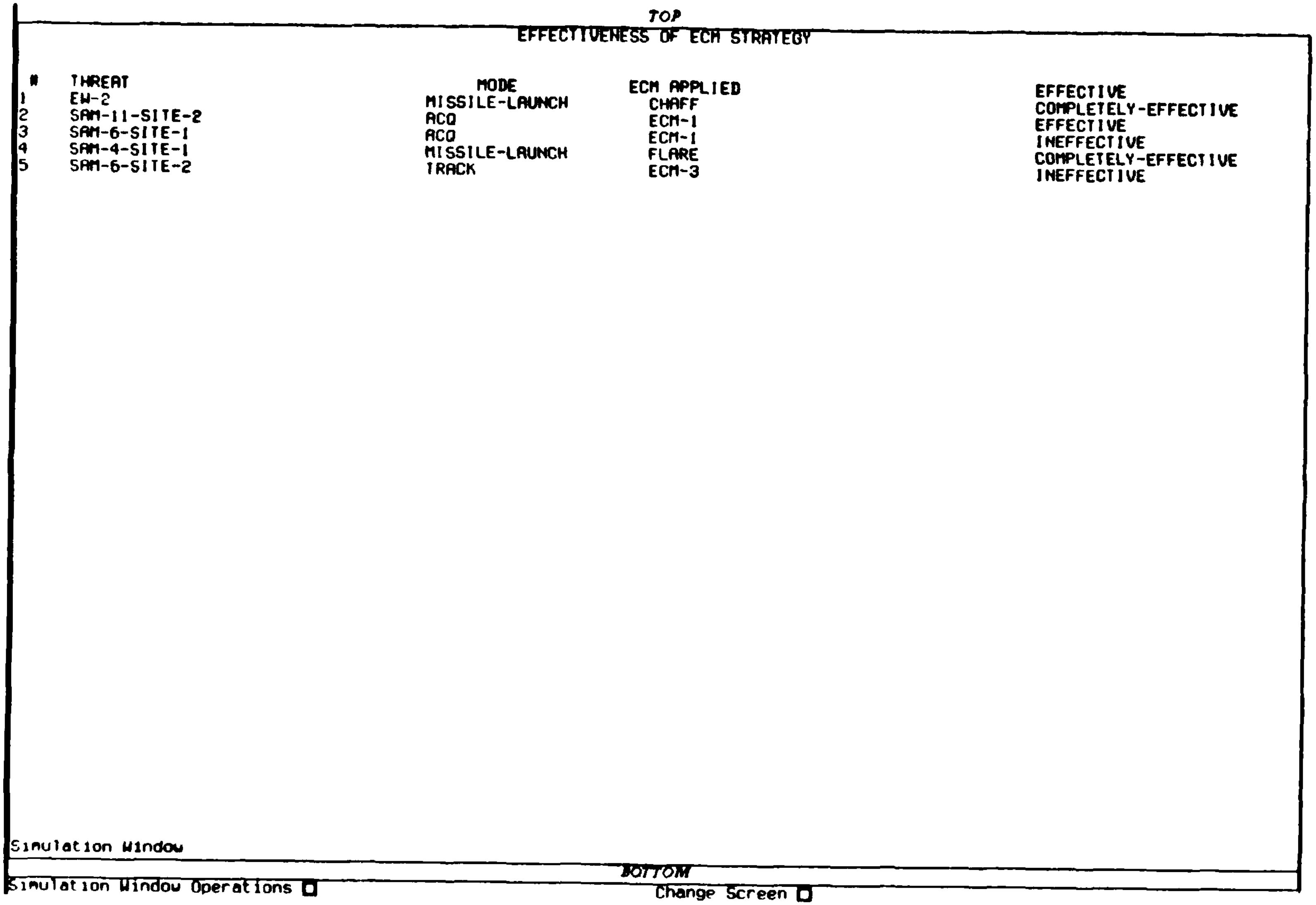
The other output of the simulation is a trace of the simulation. This is a log of when and what actions occurred during the simulation. The time of each action is logged on the left-hand side of the trace; the action fills the remaining space. The types of actions recorded is when the applied ECM changes, how effective is the ECM at a given point in the simulation, and which threats are being warned. Figure 10 is an example of a simulation trace.

A Simulation Explanation Capability. An explanation facility is also implemented into the search to allow the pilot to query the reasoning process. This facility explains the effectivity of a certain ECM technique against the threat. As previously mentioned, the explanation capability is extremely important in winning the confidence of the pilot. The pilot may not accept the displayed effectivity without a reason why. This explanation facility provides a window into the inference network of the

knowledge base. The pilot can peer into the window to better understand the reason for the effectivity.

The execution of the explanation facility is implemented the same way as the search explanation. The lines in the simulation window are also mouse-sensitive. Each numbered line in the window is mouse-sensitive. While the line is selected (boxed), a left click on the mouse will generate an explanation of the effectivity of the ECM on that line using text (See Figure 11). If the pilot clicks the middle button of the mouse once while a line is selected, an graphical representation of an inference network is displayed (See Figure 12). Both forms of explanation relay the same information. However, the pilot may prefer one form over another. This starts the explanation process. The actual explanation is displayed to the pilot using a window that overlaps the simulation window. Once again, the specifics of how to operate the explanation facility is provided in Appendix B.

All information displayed during an explanation operation is readily available from the knowledge base. Therefore, the simulation explanation is not as complex as the search explanation but provides the requested information just the same.



#	THREAT	MODE	ECM APPLIED	
1	EW-2	MISSILE-LAUNCH	CHAFF	EFFECTIVE
2	SAM-11-SITE-2	ACQ	ECM-1	COMPLETELY-EFFECTIVE
3	SAM-6-SITE-1	ACQ	ECM-1	EFFECTIVE
4	SAM-4-SITE-1	MISSILE-LAUNCH	FLARE	INEFFECTIVE
5	SAM-6-SITE-2	TRACK	ECM-3	COMPLETELY-EFFECTIVE
				INEFFECTIVE

Figure 9. Simulation Results

```
                                   TOP
                            SIMULATION TRACE

Simulation Trace.

The number of simulation ticks per minute is 2.
Total distance traveled for this route is 476.902956 miles.

Total time required for this mission is 68.1289937 minutes.

The average speed was 420.0 miles per hour.

This simulation was run at 10/28/87 23:00:53.

TICKS                        ACTION

21       Applying the following ECM: ((CHAFF EW-2)).

21       Effectiveness of CHAFF against EW-2 is COMPLETELY-EFFECTIVE.

30       Applying the following ECM: ((CHAFF EW-2) (ECM-1 SAM-11-SITE-2)).

30       SAM-11-SITE-2 has notified (SAM-6-SITE-1 SAM-4-SITE-1) of penetrator since ECM-1 is not effective.
30       Effectiveness of CHAFF against EW-2 is COMPLETELY-EFFECTIVE.
30       Effectiveness of ECM-1 against SAM-11-SITE-2 is EFFECTIVE.

31       Applying the following ECM: ((CHAFF EW-2) (ECM-1 SAM-11-SITE-2) (ECM-1 SAM-6-SITE-1)).

31       SAM-6-SITE-1 has notified (SAM-4-SITE-1 SAM-6-SITE-2) of penetrator since ECM-1 is not effective.
31       Effectiveness of CHAFF against EW-2 is COMPLETELY-EFFECTIVE.
31       Effectiveness of ECM-1 against SAM-11-SITE-2 is EFFECTIVE.
31       SAM-6-SITE-1 has notified (SAM-4-SITE-1 SAM-6-SITE-2) of penetrator since ECM-1 is not effective.
31       Effectiveness of ECM-1 against SAM-6-SITE-1 is INEFFECTIVE.
32       SAM-6-SITE-1 has notified (SAM-4-SITE-1 SAM-6-SITE-2) of penetrator since ECM-1 is not effective.
33       SAM-6-SITE-1 has notified (SAM-4-SITE-1 SAM-6-SITE-2) of penetrator since ECM-1 is not effective.
34       SAM-6-SITE-1 has notified (SAM-4-SITE-1 SAM-6-SITE-2) of penetrator since ECM-1 is not effective.
35       SAM-6-SITE-1 has notified (SAM-4-SITE-1 SAM-6-SITE-2) of penetrator since ECM-1 is not effective.
36       SAM-6-SITE-1 has notified (SAM-4-SITE-1 SAM-6-SITE-2) of penetrator since ECM-1 is not effective.
37       SAM-6-SITE-1 has notified (SAM-4-SITE-1 SAM-6-SITE-2) of penetrator since ECM-1 is not effective.
Simulation Window
                                More Below
Simulation Window Operations □                Change Screen □
```

Figure 10. Simulation Trace

The ECM technique ECM-1 applied against SAM-6-SITE-1 in ACQ mode is INEFFECTIVE.
The reason for this effectiveness is described below.

The intelligence data are 4 days old and was gathered in SUNNY weather.
This makes the intelligence data CERTAIN.

The threat is a VERY-MOBILE threat in a FLAT area.
This makes the mobility aspect of the mission against this threat VERY-UNCERTAIN.

This threat was warned of the approaching penetrator by SAM-11-SITE-2 since the ECM applied against SAM-11-SITE-2 was EFFECTIVE.

Also, the threat has the following ECCM capabilities: (NONE).
Since ECM-1 was used against this threat, the certainty of how effective ECM-1 was CERTAIN.

This makes ECM-1 INEFFECTIVE against SAM-6-SITE-1 in this situation.

If this is not acceptable, either replan your route or obtain an intelligence update or incorporate a SOJ into your plan using the 'plan' option of the map.

Explanation Window
Exit this window

Figure 11. Textual Simulation Explanation

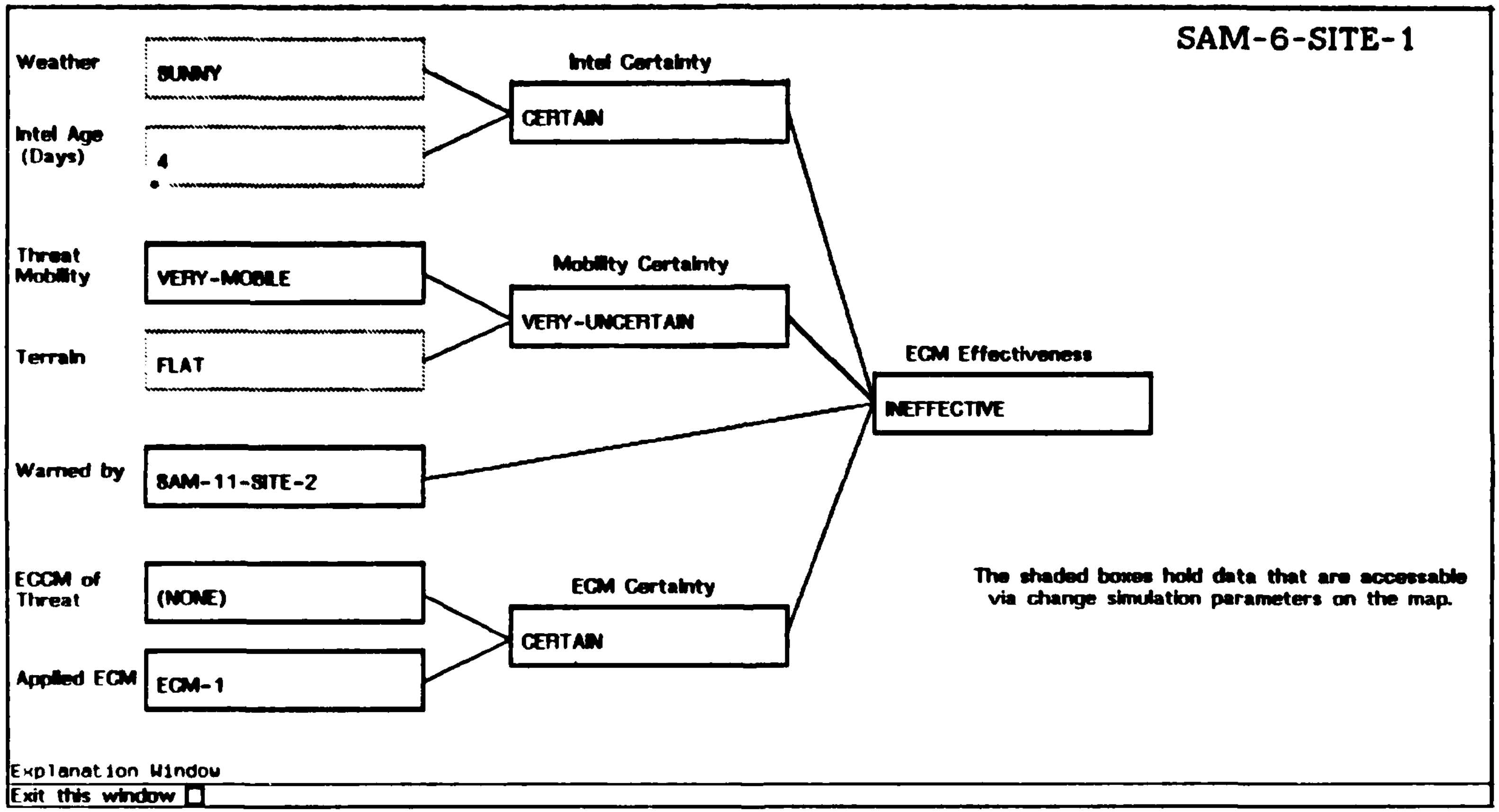


Figure 12. Graphical Representation of the Simulation Explanation

Summary

The detailed design presented in this chapter built on the conceptual design presented in chapter III. Many aspects of the conceptual design were implemented into a working, interactive tactical mission planner.

The interactive mission planner increases the pilot's situational awareness by allowing him to plan the mission using his preferences. The planner keeps the pilot in the planning loop thereby briefing the pilot as he plans the mission.

The search and simulation capabilities discussed in this chapter will increase the situational awareness of the pilot by allowing him to closely monitor the selection of a plausible ECM strategy and the determination of the effectiveness of the strategy. The search finds a plausible ECM strategy against a threat environment given the pilots preferences and the threat environment. Then the simulation determines the effectiveness of the ECM strategy by flying the aircraft against the threats applying the ECM strategy and allowing the objects of the simulation to interact. The simulation reasons about the uncertainty of the threat environment while determining the effectiveness of the ECM strategy.

The planner supports an explanation capability for the search and the simulation. The explanation capabilities increase the pilot's confidence in the recommended strategies and effectiveness determinations by providing the reasoning behind the selections.

V. System Analysis

This chapter presents an analysis of the system developed during this research. The analysis is broken into two sections. The first section discusses the overall system, its strengths, and its weaknesses. The second section addresses the evaluation of MU.

System Evaluation

This research integrated four explored ideas into a planning system conducive to tactical mission planning. This planning system was evaluated by electronic warfare engineers and a former Wild-Weasel Air Force pilot. Also, the researcher performed an evaluation of the four 'good' ideas. The results of these evaluations are presented in this section.

The system was evaluated using qualitative validation. Validation is a part of evaluation; evaluation is interested in determining a system's overall value (O'Keefe, 1987:81-82). Qualitative validation was selected based on the absence of readily available quantitative metrics. "Qualitative validation employs subjective comparisons of performance" (O'Keefe, 1987:85).

Three common approaches to qualitative validation were used -- face validation, sensitivity analysis, and visual interaction (O'Keefe, 1987:85-87). These approaches are

discussed in this chapter. However, other criteria were used during the evaluation process. These criteria include:

1. general performance of the four explored components of the system,
2. design decisions,
3. expansibility of the system,
4. maintainability of the system, and
5. the development environment.

These criteria are discussed in this chapter. In addition to these criteria, the system had to be usable.

Performance. The planning system developed for this research effort received promising evaluations. All participants in the evaluation process (electronic warfare engineers, pilots, and instructors) as well as defense contractors that saw the system during demonstrations at a conference were surprised at the capabilities of the system. The following sections discuss the performance evaluation of the capabilities of the planning system. More specifically, a face validation is performed on the four elements. Face validation is the process in which knowledgeable users "subjectively compare system performance against human expert performance" (O'Keefe, 1987:86). Each element evaluated is presented along with results pro and con.

Interactive Planner. The interactive planner used for this research proved to be a robust and very useful tool. The interactive characteristic of the planner

provided a rich environment to create threat environments as well as plan a mission route. Since the user had complete control over threat placement on the map, he was able to set up the threat environment. This allowed the user to study each threat if necessary. However, the ability to save threat environments to a file for future use also proved to be a valuable asset.

Another valuable asset of the planner is the capability to alter the threat environment or mission route and perform a search and simulation to determine the effectiveness of the ECM. The user is able to modify any aspect of the plan or threat environment to observe the consequences to the ECM effectiveness. This capability is available due to the iterative nature of the planner. The user is able to perform contingency evaluations because of the iterative capability. If the user is not satisfied with the results of a plan, he can change some aspect of the plan and re-evaluate the plan. This aspect of the planner proved to be well received by the electronic warfare engineers. The engineers exercised this capability while performing 'what if' planning. After the effectiveness of an ECM strategy was determined, the engineers would work the 'what if' question by modifying either the threat environment or the mission route and then determine the new effectiveness of the strategy.

The pilot appreciated the route planning environment. He commented on the usefulness of plotting waypoints. More specifically, he appreciated the implementation of how a partial route is displayed. Instead of allowing the user to select waypoints and then draw mission legs, the planner draws a mission leg from the last selected waypoint to the mouse pointer. This allowed the pilot to gauge how close he will fly by a threat while he is selecting his waypoints and not after.

The time required to plan a complete mission typically never exceeded three minutes.

Although the planner provided a rich planning environment, some deficiencies were noted. First, the planner was limited to one map -- Nellis AFB. This presents a problem for pilots planning missions other than Nellis. Additionally, since the map is a terrain map, most users of the system tried to exploit terrain masking during the planning process. The system does not handle terrain masking. Another comment of the pilot is the scale of the map. The scale prevented the pilot from choosing a precise waypoint. For example, the pilot was able to choose a waypoint. However, the scale of the map prevented him from knowing exactly what to look for at that waypoint. A zoom-in capability was recommended as a remedy.

Search. The constraint-directed search incorporated into this thesis demonstrated its power. The search exploited the local knowledge of the domain to derive a plausible ECM strategy to use against the threat environment. Using its two-pass facility the search was always able to find a strategy. This was preferred over having the search simply stating a solution was not obtainable.

Contingency evaluation is also supported by the search and was recognized as a valuable asset. Three facilities of the search provide means of exploring alternatives. The first facility is the ability to change the search priority. This is supported by allowing the user to change the order in which threats are searched. This is discussed in greater detail in chapter IV. The second facility to support contingency evaluation is the ability to change the recommended ECM techniques to use against a threat. If the user wishes to explore various combinations of ECM techniques, the search provided this facility. The third facility is the capability of executing the search after the configuration of the aircraft is altered. For example, the number of expendable ECM resources is modifiable using the Stores Management System (SMS). This allows for different aircraft configurations.

The explanation capability of the search proved to be a valuable asset. This facility was used by the user to verify violated constraints. However, the verbiage used in the actual explanation warranted comment by the pilot. The pilot suggested orienting the verbiage more for a pilot. The mouse-sensitive items of the search window provided a quick and accurate means of activating the explanation facility. The previous explanation interface, a pop-up window, proved to be too laborious and prone to error.

Another facility of the search that received comments is the hard copy capability. Once a plausible ECM strategy is found, a hard copy of the strategy is easily obtainable. This hard copy contains the activation times for the various ECM resources and is valuable during the simulation.

The time required to complete a search depends on the constraints of the environment. Typically, a search of 15 threats took less than one minute. However, as the number of threats increases, so does the time. A search of a large search space, 40 threats for example, may take as much as ten minutes, again depending on the constraints.

Simulation. The knowledge-based simulation determines the effectiveness of the ECM strategy generated by the search. The simulation provided a valuable means of determining the effectiveness.

Visual interaction validation was used to evaluate the simulation. This form of validation "provides visual

animation of expert system workings and allows experts to interact, altering parameters as desired" (O'Keefe, 1987:87). In addition, visual interaction "has been successfully employed in validating operations research models -- particularly discrete-event simulations" and is particularly useful for validating "graphical interfaces to knowledge-based systems" (O'Keefe, 1987:87).

Since the simulation is not as interactive as the planner or the search, the evaluation comments are limited. However, the comments provided as a result of the visual interaction were valuable. The first comment deals with displaying the ECM technique being applied at any given time on the map. This is not supported at this time. However, a trace file is used to capture this information. Instead of displaying the techniques as they are applied, the simulation records this information to the trace file for future reference.

The users appreciated the use of a small aircraft icon to gauge the progress of the simulation. This aircraft provides psychological feedback to the user. In other words, the user is not left guessing about what is going on with the simulation. With a glance the user can determine how far the simulation has progressed.

The explanation capability of the simulation provided a window into the reasoning process of the simulation. An explanation can be presented in two forms -- text and an

inference network. Although the same information is presented to the user in both forms, the inference network seemed to convey the greatest amount of information in a glance. The reasoning process was easier to understand through the network. Some users described the network as impressive. The mouse-sensitive items of the simulation window also provided a quick and accurate means of activating the explanation facility. Once the effectiveness of the ECM techniques were displayed, the engineers suggested advising the user on how to increase the effectiveness. This is done to a degree, but not to the level recommended by the engineers.

Uncertainty. The uncertainty of the planning system is incorporated in the MU knowledge base. The simulation used the uncertainty to determine what to do next. Therefore, the uncertainty is a hidden element of the planning system; the user does not interact with uncertainty per se. The simulation is the interface between the user and the uncertainty since the simulation exploits the uncertainty to determine what step to take next based on uncertain knowledge. Therefore, the simulation represents how the uncertainty affects the environment. The section titled 'MU Evaluation' later in this chapter discusses the uncertainty issues.

A sensitivity analysis is done by varying "input variable values and parameters over some range of interest and observing the effect upon system performance" (O'Keefe, 1987:86). This form of validation is "highly appropriate for systems using uncertainty measures" (O'Keefe, 1987:87). An abbreviated sensitivity analysis was performed on the uncertainty parameters. An exhaustive analysis was not performed due to the time limitation of the thesis; a complete analysis would have required an excessive amount of time. However, the analysis that was performed indicated some sensitivity anomalies. Varying some of the parameters caused the effectiveness of the ECM techniques to vary in unacceptable increments. Fortunately, the combing functions in MU that affect the sensitivity are easily modifiable. This provides a means to tune the system to an acceptable sensitivity.

<u>General Performance Issues.</u> The interfaces between the planning system and the user have gone through several iterations. The current interface has proven to be mostly user friendly. However, this has not always been the case; an earlier interface left the user guessing in several situations. For example, while planning the mission on the map, the user had to select options from different options of the map. This forced the user to jump between various menus at specific times during the planning process. This proved to be confusing and not readily apparent. The

current interface still does not completely lead the user through the planning process, but it is much better than its predecessor. Displaying only germane options during the planning process alleviated the confusion of which option to select.

Since this system is to plan tactical missions, the time required to plan is critical. A competent user can learn the planning system within one to two hours. Once the system is understood, a complete plan can be generated within five to eight minutes depending on the user and the complexity of the mission.

The planning system uses simulation ticks to measure time. These ticks are displayed to the user during the search and simulation. Some users preferred an actual time display instead of the simulation ticks.

Design Decisions. The design methodology used for the development of this research is rapid prototyping. Rapid prototyping allowed the system to be developed to meet the needs of the users in increments. This is important when the system developer is not completely familiar with the domain. The electronic warfare engineers provided the knowledge required to complete the system. Therefore, as the system grew the engineers were able to evaluate its performance. This identified problems or misinterpretations early in the development of the system thereby preventing

large rewrites of software. This methodology allows the developer to satisfy the user's requirements while keeping the user in the development process.

The TMP developed by Bradshaw (Bradshaw, 1986) represented objects in Flavors. However, MU represents objects using frames. This planning system utilizes both representations. Some objects are represented completely in Flavors and some objects are represented using a hybrid approach -- Flavors and frames in MU. This representation was adopted for its economical appeal. Representing all objects using frames would have entailed a major rewrite of software whereas representing all objects in Flavors would have defeated one purpose of the thesis -- use MU. An analysis of the two representations reveals that representing objects using frames in MU is more efficient due to the support tools of MU.

Expansibility. One of the considerations of this planning system is the ability to expand. Expansion can include handling more threat types and more ECM techniques. These expansions are easily made simply by adding the additional elements to the appropriate lists. In fact, the researcher knows of no limitations to the expansibility of this system. Simple additions to lists within the lisp code or to the MU knowledge base should provide the expansion capability for most applications.

Maintainability. Maintainability is a serious consideration for any system. If the system cannot be maintained, it will most probably become obsolete before its time. This system was developed with maintainability in mind. The software development tools of the TI Explorer were exploited to create maintainable code. The capability to create and maintain a 'system' on the Explorer is supported using the system feature. This feature maintains an up-to-date copy of the lisp code as an entity. Therefore, if a portion of the code is modified, a new 'system' is created. This facilitates maintaining software.

Development Environment. The hardware chosen for this research was the TI Explorer. This selection proved to be a good one. Since the Explorer does not provide for a second monitor thereby preventing the use of the same, this system can be distributed to any Explorer owner and not limited to only those owners that also owned a second monitor. Furthermore, the Explorer is less expensive than a Symbolics machine. Therefore, the argument can be made that more Explorers are owned by contractors. This increases the potential dissemination. The engineers agreed with the selection of the Explorer.

The Explorer was not the panacea for this problem however. The Explorer used for this research is limited to monochrome graphics. Since most planning operations are performed on the map, this actually detracts from the

planning process. Map readability is limited. This is most apparent while modifying the mission route. Selection of a leg on the route depends on the user witnessing the leg changing from a solid line drawn using an xor function to a dashed line drawn using an xor function. This transformation is not readily noticeable unless the user is careful.

MU Evaluation

Managing Uncertainty (MU) proved to be a powerful tool well suited for a knowledge-based simulation. This section discusses some of the characteristics of MU and how these characteristics affected this research.

Ease of Operation. One of MU's stronger assets is a frame-based editor. This editor allowed quick and easy modifications or creations of frames. This facility supported the design methodology of rapid prototyping; modifications recommended by the users were easily made. One drawback the researcher noticed is the time required to load the knowledge base. After the knowledge base was completed, the entire system required one hour to load. This limited the productivity of the research during system development. However, once the final product was finished, the system was loaded on a load band. This removes the requirement to load the knowledge base thereby decreasing system load time from one hour to a few minutes.

__MU's Performance.__ MU facilitated easy development of a robust knowledge base. The inheritance capability of MU made object definitions manageable. Instead of entering the same information repetitively, MU handled the inheritance of data to children. The ability to attach features to any object in the knowledge base lead to robust definitions of objects. All characteristics of the objects were implemented using features. However, combining functions underlie the true power of MU.

The combining functions were an effective means of simulating interacts amongst the simulation objects. The combining functions provided the required control structures to work the uncertainty issue. MU would use combining functions to determine what to do based on some uncertainty. This aspect of MU made it a power tool for this application. The ability to attach multiple combining functions to objects creates objects that are capable of reasoning about multiple sources of uncertainty. However, some problems do exist with combining functions.

One drawback to the combining functions in general is the format. In order to propagate values and commands throughout the knowledge base, a rigid rule-like syntax was required of the combining function. This syntax hindered the use of complex combining functions due to the limited control structures. However, there is also the capability to use lisp statements as combining functions. This removes

the control structure limitations but reveals a new limitation. Lisp combining functions will not automatically propagate values and commands throughout the knowledge base easily.

MU was evaluated based on its merits of release three. However, a release four has been developed and corrects the combining function limitations discussed. Lisp combining functions are capable of propagating values in release four. Unfortunately, the release occurred too far into the development of the mission planner to warrant learning the new release and creating a new knowledge base. Therefore, the mission planner was developed using release three of MU. Consequently, release three is evaluated in this research and not release four.

Knowledge Representation. The use of frames in MU is a natural representation. The planning objects such as threats and aircraft are viewed by the users as objects or entities. Frames allow the system developer to create objects and associate with this object knowledge in the form of features and combining functions. This representation of knowledge seems natural. Knowledge about the object and how the object responds to uncertain data in maintained within the object.

Expansibility. MU supports expansibility. It can be updated to include virtually any number of objects. However, MU requires all objects be declared interactively.

In other words, objects cannot be dynamically instantiated. This places a limitation on the number of objects in the plan and simulation. This did not hinder this research since dynamic instantiation was not required. However, all objects had to be declared before the system was run. Therefore, the number of threats that can be placed on the map is limited. This was not a problem for this research but an operational system will most likely require dynamic instantiation of objects.

Summary

The planning system developed during this research is analyzed using various validation techniques. The strengths and weakness of the system are discussed. A technology assessment of MU is performed and discussed. This planning system satisfies the user's requirements and as such provides a powerful planning tool.

VI. Conclusions and Recommendations

Conclusions

The tactical mission planner developed during this research effort demonstrates the feasibility of applying artificial intelligence techniques to the process of mission planning.

Two AI techniques were incorporated into the planner. The first technique was a constraint-directed search. The search proved to be an effective tool to generate a plausible ECM strategy to use against a threat environment. By pruning paths from the search that represented violated constraints, the search was able to find the strategy without suffering from the combinatorial explosion commonly found in search-type problems. The search considered the constraints of the aircraft (e.g. limited number of expendables and limited power for jammers) in addition to the capabilities of the threats to determine the ECM strategy to employ against the threat environment. Since the constraints of the search (aircraft and threats) are modifiable using the facilities of the system, the search also served as a contingency planner for the ECM strategy.

The explanation capability of the constraint-directed search increased the user's confidence in the ECM selection.

This facility provided the reasoning behind a certain selection upon request.

The second AI technique implemented in this research effort is a knowledge-based simulation. The simulation also demonstrated its usefulness in mission planning. The simulation increases the situational awareness of the pilot by allowing the pilot to view how the threat environment will react as he applies the ECM. He is capable of detecting areas of concern based on the simulation results since the effectiveness of the ECM techniques is displayed to the pilot.

Simulating the recommended (produced by search) ECM strategy also proved to be an effective tool for the electronic warfare engineer. Since the engineer was able to alter the characteristics of the threats and the ECM techniques, the simulation can be used as a design aid. The knowledge base can be updated to include any new ECM techniques or new threats thereby allowing the engineer to verify how the objects will interact.

The knowledge-based aspect of the simulation is an excellent representation of the simulation objects. The knowledge base representation was natural for the objects. Each object was represented by its characteristics and how it can interact with other objects.

The explanation capability of the knowledge-based simulation increased the user's understanding of why the ECM was determined to be as effective as it was. This facility described the reasoning that occurred to obtain the indicated effectiveness.

Reasoning about uncertainty is a necessity for tactical mission planners that reason about the effective allocation of electronic warfare resources. EW has been shown to be a perfect paradigm of an uncertain domain. The mission planner developed for this research effort exploits the uncertainty of domain to determine the true effectiveness of recommended ECM strategies.

Managing Uncertainty (MU) proved to be a powerful tool well suited for a knowledge-based simulation. MU's capabilities facilitated rapid prototyping of a knowledge base.

MU was evaluated based on its merits of release three. However, since release four has been developed and corrects some limitations, MU should be judged for its new merits. Lisp combining functions are among the improvements of release four. The new capabilities of these combining functions are discussed in chapter V and should provide a powerful way to implement control when uncertain.

Recommendations

The building and subsequent evaluation of the tactical mission planner has prompted discussions between the researcher and various individuals. These discussions have produced several ideas for improving the planner. Those ideas and issues that warrant further research are presented in this section.

Operational Considerations. The mission planner developed for this thesis should be incorporated into an operational setting for further evaluation by fighter pilots. This would allow the pilots to determine the benefits of using this mission planner with its associated capabilities.

The planner should also be placed in the Avionics Laboratory, Electronic Warfare Division for further evaluation as a EW design tool. Once the planner is on an appropriately certified computer system, the planner can be upgraded to include classified data. This would provide the engineers of the lab an opportunity to verify real ECM techniques against a real threat environment.

Hardware Considerations. The tactical mission planner was developed on a TI Explorer using the MU knowledge base. MU presently requires KEE for operation. This environment is extremely expensive (over $100,000) and typically beyond the budget of the recommended operational deployment locations. Therefore, the software needs to be ported to a

different, less expensive, computer system such as the Zenith Z-248 equipped with a Humming Board. This configuration should satisfy the memory requirements. Since this configuration is readily available to virtually all Department of Defense agencies and is considerably less expensive than the TI Explorer, the distribution of future versions of the tactical mission planner will not be as restricted as it is now.

However, if the mission planner is to remain on the TI Explorer, a color monitor should be added to the system thereby providing two monitors to display information. This concept has been demonstrated by the previous two tactical mission planners. The pilot will spend less time switching between windows and increase his productive time at the planner. Since the monitor is color, details of the map will be more apparent to the pilot. Also, areas of greatest danger can be signaled using an appropriate color.

Exploiting the abilities of parallel processing should benefit the planner. Instead of displaying the threat environment as a group of circles and forcing the pilot to find the areas of greatest danger by inspecting the circles, an array processor could be used to display a danger indices map. Due to the size of the map and the time required for calculations of this nature, a single processor machine will be slow for this application. This map would represent the various danger levels of the map with different shades of

gray or colors. Also, as the altitude of the aircraft changes during the planning process, the map changes to reflect the danger indices at that altitude. An effective and safe route could be as easy as avoiding all red areas for example.

Map Considerations. The next version of the tactical mission planner should implement a terrain masking algorithm. All information required for this type of algorithm currently exists. The terrain masking will provide the pilot with a more realistic threat environment representation. The researcher has noticed that all pilots using the planner rely on terrain masking as a means of combatting the threats.

The current planner reasons about all threats in the threat environment regardless of how close they are to each other. For example, if two identical threats are located virtually in the same location, the current planner reasons about two distinct threats. However, since the two threats are so close, they may be able to be considered as one slightly larger threat. This may be the way a pilot actually reasons about threats. The larger threat decreases the number of threats the search must reason about and thereby decreases the speed of the search. This concept can be used to group several threats.

The map should support a zoom capability. This capability would allow the pilot to zoom in to a location on the map. This allows the pilot to select terrain features to look for during the mission. Therefore, the pilot will have a mental picture of the terrain at a given location, typically a waypoint. This increases the situational awareness of the pilot.

Another recommendation is the use of three-dimensional graphics. This would once again increase the situational awareness of the pilot by providing a pilot's view of the terrain. The pilot will know what to expect.

ECM Considerations. The current planner does not deploy expendables in patterns. Instead one expendable is deployed when requested. Upgrading the expendable delivery methods should be performed to allow patterns and thus make the planner more realistic. Also, provisions should be made for faulty expendables. The planner currently assumes that once an expendable is deployed it functions properly. This may not always be true.

The ECM jammers are also assumed to be completely operational for the duration of the mission. Data pertaining to the mean time between failures of the jammers should be incorporated into the planner. In order to develop a realistic design tool, the ECM techniques would have to be modified. The current system only allows one ECM technique per threat. A realistic system may recommend

multiple techniques to combat threats. Also, the techniques may be more effective if multiple jammers were used such that a jammer may in effect jam more than one threat. This capability warrants further research.

The simulation determines the effectiveness of the ECM strategy and offers generic recommendations for how to improve the effectiveness of all techniques. However, recommendation capability for a specific ECM technique is not supported. A future system should provide means of suggesting how to improve the effectiveness of a specific technique. Furthermore, the critiquing process could be modified. Since critiquing plans can be performed by an expert, perhaps a better approach to critiquing the plan (ECM strategy and mission route) would be to build an expert system.

Since some fighter aircraft currently possess the capability to load navigational data onto a tape from the planning computer, the ECM strategy could be loaded also. Once the strategy is loaded into the aircraft, it would control the ECM systems of the aircraft. However, the pilot's consent would be required for ultimate execution of techniques. This keeps the pilot in the loop.

Summary

Applying artificial intelligence techniques to the mission planning domain has produced a working ground-based tactical mission planner capable of planning offensive counter air missions. A constraint-directed search determines the most effective ECM strategy to use against a threat environment. A knowledge-based simulation determines the true effectiveness of the recommended strategy by reasoning about uncertainty of the domain while performing a simulation. Artificial intelligence techniques show promise in the future for mission planning systems.

The planning system can increase the situational awareness of a pilot as his plans his mission by providing interactive tools that keep him involved in the planning process. The pilot is free to concentrate on the mission objectives while the planning system performs the low-level tasks. The simulation creates a mental picture of how the threats will react to ECM for the pilot. These mental pictures and the time to think about the higher-level mission tasks increase the pilots situational awareness thereby increasing the probability of a successful mission.

Appendix A: Acronyms and Terms

AAA: Anti-Aircraft Artillery.

AFB: Air Force Base.

AFIT: Air Force Institute of Technology.

AGL: Above Ground Level.

AI: Artificial Intelligence.

ARM: Anti-radiation Missile.

Bel: Belief function (used in Dempster-Shafer theory).

C3CM: Command, Control, and Communication Countermeasure.

CA: Counter Air.

CAS: Close Air Support.

CC: Command Center.

CF: Certainty Factor (used in Dempster-Shafer theory).

Chaff: Thin, narrow metallic strips of various lengths used by tactical aircraft to confuse hostile radars.

DARPA: Defense Advanced Research Project Agency.

DMA: Defense Mapping Agency.

EC: Electronic Combat.

ECCM: Electronic Counter-Countermeasures.

ECM: Electronic Countermeasures.

EKSL: Experimental Knowledge Systems Laboratory.

Electromagnetic Spectrum: The range of frequencies generated by electromagnetic radiation.

EMCON: Emission Control.

EOB: Electronic Order of Battle (A list of all electronic warfare equipment including type,location, and other important data).

ERP: Effective Radiated Power.

ESM: Electronic Warfare Support Measures.

EW: Electronic Warfare.

EWO: Electronic Warfare Officer.

EWR: Early Warning Radar (Long range radars used to detect enemy aircraft).

FEBA: Forward Edge of the Battle Area.

FRL: Frame Representation Language.

FTD: Foreign Technology Division.

GCI: Ground-Controlled Intercept.

IADS: Integrated Air Defense System.

INT: Air Interdiction.

INTEL: Intelligence Information.

IP: Initial Point.

IR: Infrared (The portion of the frequency spectrum lying beyond the red portion of the visible spectrum. Used to detect heat for tracking purposes).

ISIS: Intelligent Scheduling and Information System.

KEE: Knowledge Engineering Environment.

KNOBS: Knowledge-Based System.

LISP: List Programming.

LLTR: Low Level Transit Route.

m: Basic probability assignment (used in Dempster-Shafer theory).

MB: Measure of Belief (used in Dempster-Shafer theory).

MD: Measure of Disbelief (used in Dempster-Shafer theory).

MIT: Massachusetts Institute of Technology.

MU: Managing Uncertainty (A tool developed by the EKSL).

OCA: Offensive Counter Air.

OUS: Operationally Useful System.

POL: Petroleum, Oil, and Lubrication.

RADAR: Radio Detection and Ranging.

RADC: Rome Air Development Center.

REC: Radio Electric Combat.

RGPO: Range Gate Pull-Off.

RHAW: Radar Homing and Warning.

ROSS: Rand Object-oriented Simulation System.

RPA: Route Planning Aid.

RPV: Remotely Piloted Vehicle.

RWR: Radar Warning Receiver.

SAM: Surface-to-Air Missile.

SMS: Stores Management System.

SOJ: Stand-Off Jamming/Jammer.

SRL: Schema Representation Language.

SWIRL: Simulating Warfare In the ROSS Language.

TI: Texas Instruments.

TMP: Tactical Mission Planner.

TWIRL: Tactical Warfare In the ROSS Language.

UMASS: University of Massachusetts (at Amherst).

WTCP: Westinghouse Turbine Component Plant.

Θ: Frame of Discernment (used in Dempster-Shafer theory).

$\oplus$: Rule of Combination (used in Dempster-Shafer theory).

Appendix B: The User's Manual

The planning system developed during this research effort is easy to use with a minimum amount of practice. The system is basically menu driven to facilitate a quick learning of the system. This appendix provides the information required to exercise the system effectively.

Conventions and General Guidelines

This section presents the conventions and general guidelines used throughout this manual.

Commands entered either from the keyboard or the mouse are placed in double quotes. This means either type the quoted information on the keyboard or click the mouse on the quoted element. A carriage return is depicted as <cr>. Clicking the mouse refers to pressing and releasing a mouse button. Which button to click is given in the command. For example, a right click means click the right button of the mouse once. A double right click means click the right mouse button twice in rapid succession. If the button is not specified, click any button. An important issue concerning the mouse is precision. In order to maintain precision in the system, the user should attempt to click the mouse only when the mouse is not moving. Clicking the mouse while the mouse is moving reduces precision by smearing the click.

Run bars are horizonal lines approximately 1/2 inch long located at the bottom of the screen. These bars indicate the system is performing an operation. Although not necessary, it is recommended to wait until the run bars stop flashing until proceeding to the next operation.

Windows

The window immediately above the run bars is in reverse video and is called the mouse documentation line. As the name implies, this window describes what operations will be performed when the specified mouse button is clicked. This window will change depending on the current state of the system and should be monitored to help the user learn the system.

The window immediately above the mouse documentation line is a status window. This window explains the current process and provides guidance in some situations. This window should be monitored and followed throughout the planning process. This is especially true for new users that are unfamiliar with the system. This window will help the new user learn the system. Also, the window can be used as a lisp listener simply by clicking the mouse inside of it.

Various other forms of windows are used in this system. Learning how to interact with these different forms of windows will increase the user's planning abilities. The

most common window used is the pop-up window. This form of window does not have margin options. Figure 13 illustrates this type of window. Pop-up windows are used to select one option from a list of options. To select one of the options, place the mouse pointer over the desired option until this option is boxed and then click the left mouse button. To remove the window from the screen without making a selection, simply move the mouse pointer inside the window and then outside. The window disappears from the screen.

Threat Operations		
Move Threat	Save Threats	Delete Threat
Delete ALL Threats	Place SA-1	Place SA-2
Place SA-3	Place SA-4	Place SA-5
Place SA-6	Place SA-7	Place SA-8
Place SA-9	Place SA-10	Place SA-11
Place SA-X-12	Place S-60	Place ZSU-23-4
Place 12.5MM	Place 37MM	Place EW Radar
Place CC		

Figure 13. Pop-up Window

Another form of window used in the system is a variable value selection window. This window is identified by the margin choices at the bottom of the window. These choices include "Do it" and "Abort". Figure 14 illustrates this form of window.

```
SAM-6-SITES
MISSILE-LAUNCH-ABOVE:  (DECOY CHAFF)
MISSILE-LAUNCH-IN:     (CHAFF DECOY ECM-4)
MISSILE-LAUNCH-BELOW:  (FLARE ECM-4)

TRACK-ABOVE:           (ECM-3 DECOY CHAFF)
TRACK-IN:              (ECM-3 CHAFF DECOY)
TRACK-BELOW:           (ECM-3 ECM-2)

ACQ-ABOVE:             (ECM-2 CHAFF DECOY)
ACQ-IN:                (ECM-1 ECM-2 CHAFF DECOY)
ACQ-BELOW:             (ECM-2 ECM-1)

SURV-ABOVE:            (ECM-1)
SURV-IN:               (ECM-1)
SURV-BELOW:            (ECM-1)
Do it □                        Abort □
```

Figure 14. Variable Value Selection Window

Once this type of window is exposed, one of the margin choices must be selected or the "Abort" key pressed to de-expose the window. This type of window is used to change multiple values. To change a value inside the window, the user should place the mouse pointer on the value to change. The value will become boxed. The user should then click the left mouse button. The window will either display a pop-up window or await input from the keyboard. If a window pops up, the user should select the appropriate value. If a menu does not pop up, the user should enter the new value from the keyboard ending the entry with <cr>. After all changes are made and the values are acceptable, the user should select the "Do it" margin choice. Selecting an options is accomplished by placing the mouse pointer in the choice box

until the mouse pointer turns into an 'X' and then clicking the left mouse button. This will make the appropriate changes. If, however, the user is not satisfied with the values, the user should select the "Abort" choice. This will abort the window without making changes.

Mouse-confirmation windows are used to confirm a requested operation before the operation is performed. The user should simply follow the instructions inside the window.

A mouse-sensitive scrollable window is used to display the search and simulation information to the user. The type of window is illustrated in Figure 15.

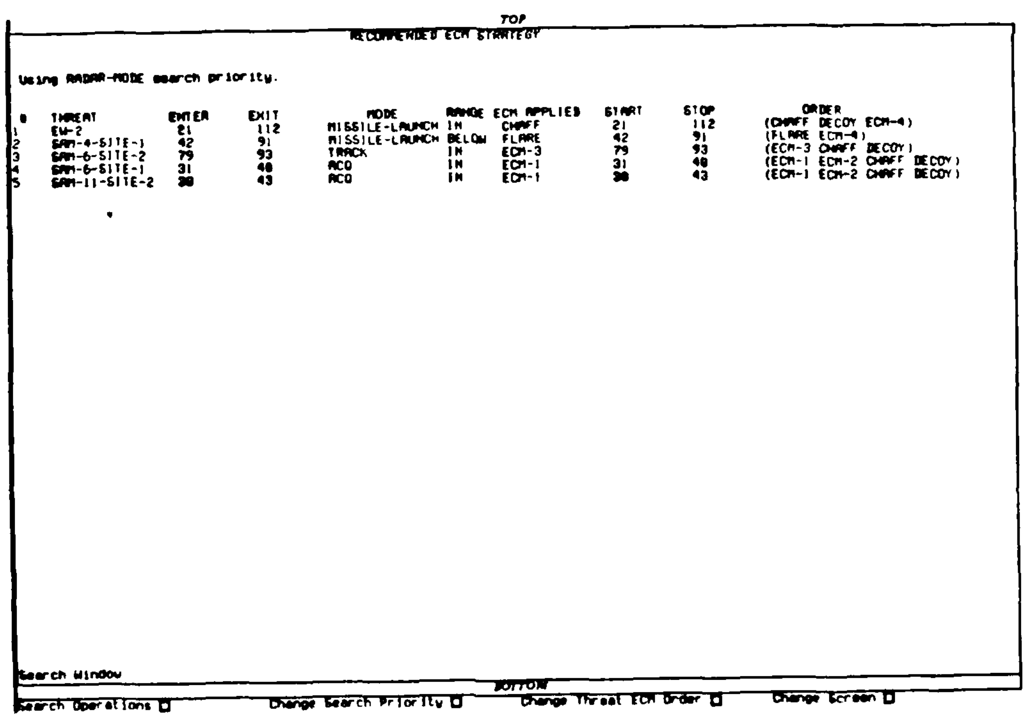


Figure 15. Mouse-Sensitive Scrollable Window

This type of window may be scrolled using two methods. The first method uses the bounce bar on the extreme left-hand side of the window. This bar is thicker than the other three borders of the window and indicates the relative percentage of information being shown to the user. For example, if the bar is solid the entire length of the window, all information is being displayed to the user. However, if the bar is solid only a portion of the length of the window, some information is not visible to the user at that instant. To scroll the window, the user should bounce the mouse pointer against the bounce bar until the pointer turns into a double pointing arrow. This arrow points up and down. The user is now ready to scroll and should simply follow the mouse documentation line for further instructions.

The second method of scrolling this type of window involves the top and bottom margins. These two margins indicate if more information is either above or below. If more information is below for example, the bottom margin will read "More Below". To scroll the window down to the new information, the user should bounce the mouse pointer against the words "More Below". This will change the mouse pointer into a down arrow and scroll the window one line at a time. To scroll an entire page, the user should follow the mouse documentation line while the pointer is an arrow.

Similarly, the window can be scrolled up using the same technique with the "More Above" margin.

System Recovery

If the system enters a state in which the computer does not respond to input from the keyboard or from the mouse, the user should follow these steps until the system responds:

1. Press the "Abort" key.

2. While holding down a "Control" key, press the "Abort" key.

3. While holding down both a "Control" key and a "Meta" key, press the "Abort" key.

4. While holding down BOTH "Control" keys and BOTH "Meta" keys, press the "Return" key. This will perform a warm boot.

5. While holding down BOTH "Control" keys and BOTH "Meta" keys, press the "Rubout" key. This will perform a cold boot.

Starting the Planner

Due to the vast number of configurations for load bands on the Explorer system, this appendix assumes the Explorer is turned on and is booted under the TMP load band. If this is not true, the user should boot the TMP load band using the menu load after the system self-tests.

Once the system is booted, the user should enter "(login 'mullins t)" to login the system. The planner can now be entered by pressing either the "Term" or "System" key and then "T". Another means of entering the planner is to select the "TMP" option from the system menu. The system menu is exposed by a double right click on the mouse at any time.

Pressing the "Term" key followed by the "Z" key toggles the speech module. The window in the bottom, right-hand corner of the screen displays the current setting of the speech module.

The system currently uses five different windows to interact with the user. These windows are the pictogram window, the map window, the SMS window, the search window, and the simulation window. All of these windows are easily accessible from any other window. This is accomplished by clicking the mouse on the "Change Screen" option at the bottom of the current window. A list of the other windows is displayed using a pop-up menu. The user should select the appropriate window. This window is then exposed.

The planner is ready when the introduction window is displayed. The introduction window contains a three-dimensional F-16. The user is now ready to start the planning operation. The user should change to the map window to begin the operation using the "Change Screen" option.

Map Window

The map is now displayed. Most planning operations are done using the map. The first thing the user should do is to begin the planning of the mission. This is done using the "Plan" option of the map. Most map operations are terminated by a right click on the mouse.

Planning Operations. Planning operations are used to create and alter the mission. These operations are accessible by using the "Plan" option of the map.

The threat information should be loaded before any other operation. The user should first select the "Plan" option of the map. A pop-up window is exposed with "Read Intelligence" at the top of the menu. The user should select this item. Another window is exposed asking for the threat file to use. This file contains the threats to be used during the planning process and where these threats are located on the map. The user can either accept the default by clicking on "Do it" or view the alternatives by clicking on the default name. Another menu is exposed with alternative threat file names if the user clicks on the default file name. The user must now select one of these alternatives. Once the threat file selection is made, the user should click on "Do it" to execute the operation of loading the threat file. As the threat file is loaded, the threats are displayed on the screen. The threats are composed of a threat designator, a lethality circle, and a

radar cone. The FEBA is also displayed at this time. After the threat file is loaded, the ECM techniques are loaded from a file. These operations take a couple of minutes. The user should watch the status window at the bottom of the screen for the current status of these operations.

The user should now select the "Load ATO" item from the planning menu. This will load the ATO. The target (a triangle in the upper left-hand corner of the map), home base (a circle in the lower right-hand corner of the map), and LLTR locations (circles between home base and the FEBA) are displayed on the map. Then the system displays the Stores Management System (SMS). This illustrates the current configuration of the aircraft. The user should refer to the section titled "SMS" for instructions on how to use the SMS. After any changes are made to the SMS, the user should go back to the map by selecting the "Map" item of the "Change Screen" option of the SMS window.

The user is now ready to select the initial point (IP). This is done by selecting the "Select IP" item from the planning menu. The status window will provide instructions on which mouse button to click. The user should place the mouse pointer at the point on the map where he would like the IP. This point should be close (with a few inches) to the target. Once the location is determined, the user should click the left button. A square is displayed at the selected location. This is the IP.

The user is now ready to plan the mission route. This is done by selecting "Build Mission Legs" from the planning menu. After this item is selected, a line is drawn from home base to the mouse pointer. As the user moves the mouse, the line follows the pointer. The status line provides direction on which mouse button to click to select a waypoint on the map. Also, the current speed and AGL of the aircraft are displayed in the map information window on the right-hand side of the screen. To change these values during the route-generation process, the user should press the "C" key on the keyboard. This provides access to these parameters via a window. The user should exit the window when the necessary changes are made. This places the user back in the route generation mode.

The user has two options from home base. He can either enter an LLTR or select his own waypoints. Entering an LLTR is recommended. If the user chooses to enter an LLTR, he should click the middle button of the mouse on one of the three closest LLTR circles. The system will automatically draw the remaining LLTR legs. The user should wait a few seconds until the system plots the LLTR route. If the user chooses to select his own waypoints, he simply clicks the left mouse button at the desired waypoint locations on the map.

When the user is ready to select the IP as the next waypoint, he should double click the middle mouse button. This will create a leg from the last waypoint to the IP and then to the target. The system may respond with a message in the Message window concerning the fuel used. The user should NOT try to select the IP and the target by any other means. This double click operation is critical to the planning process and may produce an error if absent.

The system is now ready to plan the egress route. The same process is followed to select waypoints for the egress route as was used for ingress. A left click selects waypoints, and a middle click selects an LLTR. An LLTR must be selected as the last part of the egress route. To enter an LLTR, click the middle button on one of the three LLTR circles farthest from home base. The system will automatically draw the legs between the LLTR points and home base.

The mission route is now planned. If the mission route consumes too much fuel, the screen will flash several times. Two options exist to correct this anomaly. The route may be modified using "Modify Route" of the planning menu. The other option is to change the speed of the aircraft for one of the legs using "Modify Speed AGL" of the planning menu.

If "Modify Route" is selected, the actual legs of the route are changed. Once this option is selected, the mouse pointer can be moved close to either one of the waypoints

(other than the IP, target, LLTRs or home base) or the middle of one of the mission legs (other than LLTR legs or the leg between the IP and the target). When the mouse is close to one of these items, the item will highlight itself. The highlighted waypoints are easily noticeable; however, the highlighted legs are very difficult to notice. Therefore, the user should pay particular attention to the legs as the mouse approaches the middle of the leg. Once an object is highlighted, a left mouse click will either grab the waypoint, in the case of a highlighted waypoint, or create a waypoint in the middle of the highlighted leg and grab the newly-created waypoint. Once the waypoint is grabbed, it can be moved to a new location using the mouse. Another left click on the mouse places the waypoint. This process can continue until the user is satisfied with the new route. When the user is satisfied, he should click right on the mouse to terminate the current process. This will re-evaluate the fuel constraints for the mission. If the constraints are violated again, the screen will flash and the route must be modified once again.

If the user wishes to change the speed of the aircraft instead of the mission route in order to correct the fuel anomaly, the user should select "Modify Speed AGL" from the planning menu. This allows the user to change the speed and the AGL of a mission leg (except the LLTR legs). The mouse is used the same way as modifying the mission route to

highlight a mission leg. Once a leg is highlighted and selected (left mouse click), a window is exposed near the leg and allows the user to alter the speed and AGL of the leg. Exiting this window allows the user to change these parameters for other legs as well until the user terminates this process by a right click. This click checks the fuel constraints of the mission. If the constraints are not satisfied, the screen flashes once again indicating more modifications are necessary.

If the user wishes to replan the entire route, he should select "Replan Entire Route" from the planning menu. This will erase the previous route and allow the user to plan a new route using the procedure already discussed.

At any time during the planning process, the user may wish to know the latitude, longitude, and elevation of a specific location on the map. This is done by selecting "Get Lat, Long, Elev" from the planning menu. Now using the mouse, the user can point to location on the map and then click a mouse button. The requested information is displayed to the user via the Messages window on the right-hand side of the screen.

The user may wish to incorporate a stand-off jammer (SOJ) into the mission. This is done by selecting "Add-Remove SOJ" from the planning menu. A SOJ is then added to the mission and is depicted by a message in the upper right-

hand corner of the map. The user may also remove the SOJ by again selecting the same item from the planning menu.

At any time, the planner may be reset by selecting "Reset Planner" from the planning menu. The system will then confirm the request. After confirmation, the system will reset all aspects of the planner. This operation requires a couple of minutes to complete.

Once the mission is planned and the user is satisfied with the plan and the threat environment, he should proceed to the section of this appendix titled "Simulation Operations" to perform the search and simulation. If, however, the threat environment requires modification, the user should continue with the next section -- "Threat Operations".

Threat Operations. Threat operations are used to create and alter the threat environment. These operations are accessible by using the "Threats" option of the map.

Threats may be placed on the map by selecting "Place XXX" from the threat menu where XXX represents a threat name. For example, selecting "Place SA-7" will allow the user to place a SAM 7 on the map. After selecting the type of threat to place, the user can place the threat on the map at the location pointed to by the mouse pointer by clicking the left mouse button. A threat of the type selected is then placed at the mouse location. This can continue until five threats of that type are placed. Due to the dynamic

limitations of the knowledge base, the threats are limited to five for any type except early-warning radars and command centers which are limited to two.

The user can also move the existing threats around the map by selecting "Move Threat" from the threat menu. Moving the mouse pointer close to the center of a threat causes the threat to highlight itself. Once a threat is highlighted, a left mouse click will grab the threat (the threat designator is grabbed by the mouse). The user should now move to the new desired location on the map and click the left mouse button. This will release the threat. The user may move as many threats as he wishes using this process. The threats are not redrawn until the move-threats operation is terminated with a right click.

Similarly, threats may be deleted/removed from the map by selecting "Delete Threat" from the threat menu. The threats are deleted much the same way they are placed. Moving the mouse close to the center of a threat causes the threat to highlight itself. A left or middle mouse click will delete the highlighted threat. The user may delete as many threats as he wishes using this process. A right click will abort this process. Once aborted, the system will redraw the map without the deleted threats.

If the user wishes to delete ALL the threats, he should select "Delete ALL Threats" from the threat menu. The

system will ask the user for confirmation. If the user confirms, the system will delete all threats from the map.

The user may decide to store the current threat configuration to a file for future use. This option allows the user to create a threat environment and save it to a threat file. This is the same threat file asked for during the "Read Intelligence" operation. To save the current threat configuration to a file, select "Save Threats" from the threat menu. A window will appear asking for the file name to be used. The user should provide a file name.

Display Operations. Display operations are used to alter how the map is displayed. These operations are accessible by using the "Display" option of the map and are not necessary for the planning process. The following operations are simply to allow the user to view the map differently.

The user may wish to display only the map at some point during the planning process. This is done by selecting "Terrain Only" from the display menu. Just the terrain is displayed.

To display everything except the threats, the user should select "Without Threats" from the display menu.

To display everything except the radar cones of the threats, the user should select "Threats without radars" from the display menu.

After the intelligence-gathering mission is performed, the user may wish to display only the threats the search and simulation will be concerned about. This is done by selecting "Threatening Threats" from the display menu.

To redraw the entire map displaying everything, select "Refresh Display" from the display menu. This is useful if stray lines were generated during the planning procedure.

Simulation Operations. Simulation operations are used to perform the search and the simulation. These operations are accessible by using the "Simulation" option of the map.

Once the user is satisfied with the mission plan and the threat environment, he may wish to view and possibly alter the simulation parameters. This is done by selecting "Change Simulation Parameters" from the simulation menu. The system will provide the user with a window in which the user may change the simulation parameters. If the parameters are altered, the map is redrawn.

After the simulation parameters are altered, if at all, the user should select "Generate ECM Plan" from the simulation menu. This directs the system to perform the intelligence-gathering mission and then the constraint-directed search.

Search Window

After the intelligence-gathering mission, the search window is exposed and the search begins. If the search finds a plausible ECM strategy, the strategy is displayed. If, however, the search cannot find a plausible strategy due to the constraints of the aircraft, a message is displayed to the user in the middle of the search window. The message explains that the search could not satisfy all constraints and that a second pass is required. The search then performs a second pass relaxing constraints until a strategy is found. Once this strategy is found, it is displayed in the search window. The search window is scrollable. Therefore, if the user wishes to view information not currently visible, he may scroll to the information using the instructions provided in the section titled "Windows". Figure 16 illustrates the search window with a search solution.

The first sentence in the search solution indicates which search priority was used for the search. In this case, the search priority was radar-mode. The first column of the search solution is the threat. The second and third columns indicate when the aircraft will enter and exit the threat respectively. These numbers are simulation ticks. The fourth column represents the most probable mode of the threat as the aircraft passes through it. The fifth column represents whether the aircraft was above, in, or below the

TOP

RECOMMENDED ECM STRATEGY

Using radar-mode search priority.

#	THREAT	ENTER	EXIT	MODE	RANGE	ECM APPLIED	START	STOP	ORDER
1	ew-2	21	112	missile-launch	in	chaff	21	112	(chaff decoy ecm-4)
2	sam-4-site-1	43	92	missile-launch	below	flare	43	92	(flare ecm-4)
3	sam-6-site-2	79	93	track	in	ecm-3	79	93	(ecm-3 chaff decoy)
4	sam-6-site-1	31	48	acq	in	ecm-2	31	48	(ecm-2 ecm-3)
5	sam-11-site-2	38	42	acq	in	ecm-3	38	42	(ecm-2 ecm-3)
6	sam-11-site-1	84	88	acq	in	ecm-2	84	88	(ecm-2 ecm-3)

Search Window

BOTTOM

Search Operations ☐ Change Search Priority ☐ Change Threat ECM Order ☐ Change Screen ☐

Figure 16. A Search Solution

effective altitude of the threat. The sixth column indicates the ECM recommended by the search. The seventh and eighth columns represent the recommended time tc start the ECM and stop the ECM respectively. Finally, the last column represents the suggested order of ECM techniques to use as generated by the knowledge base. This list is sorted with the most effective techniques towards the left of the list. The user may change this list using facilities of the search discussed later in this section.

The user may request an explanation of why an ECM technique was recommended by the search. This is done by placing the mouse on the line containing the ECM technique in question. This line will become boxed. A left click will generate an explanation. Figure 17 illustrates an explanation.

After the user finishes with the explanation, he should exit the search-explanation window by selecting "Exit this window". The user may obtain as many explanations as he wishes using this approach.

If the user is satisfied with the results of the search, he may obtain a hard copy of the results by simply selecting "Hardcopy" from the search operations menu.

If the user is not satisfied with the results of the search, he may decide to change the number of expendable on board the aircraft. This is done by simply changing the number of expendables using the SMS. This process is discussed later in this appendix in the section titled 'SMS'. After the number of expendables are changed, the user can re-execute the search using the new constraints -- a different number of expendables. This can be accomplished by selecting "Execute Search" of the search operations menu.

Similarly, if the user is not satisfied with the search results, he may modify the mission route. This is done by going to the map window and modifying the route as discussed earlier. If the route is altered, a new intelligence-

gathering mission must be performed by selecting "Generate ECM Plan" from the simulation menu of the map window. This allows the user to iteratively perform the search.

Another means of altering the search results is to change the search priority. This is done by selecting one of the priorities from the "Change Search Priority" option of the search window. The search is re-executed when a new priority is selected.

A facility is provided that allows the user to create or modify the suggested ECM techniques provided by the knowledge base (the last column of the search results). These techniques are represented as lists within the knowledge base and are easily modified. This is done using the "Change Threat ECM Order" option of the search window. After this option is selected, a window is displayed. The user should select "Update an ECM Technique in the KB" which causes the system to expose another window. This window asks the user what type of threat (SAM, AAA, or radar) he would like to work with. After the user selects the type of threat, the system displays a window with the threats of the selected type. For example, if SAMs were selected, all types of SAMs are displayed. The user then selects which threat he wishes to alter from this window. Once the threat is selected, another window is exposed that provides the user with access to the various recommendation lists. The

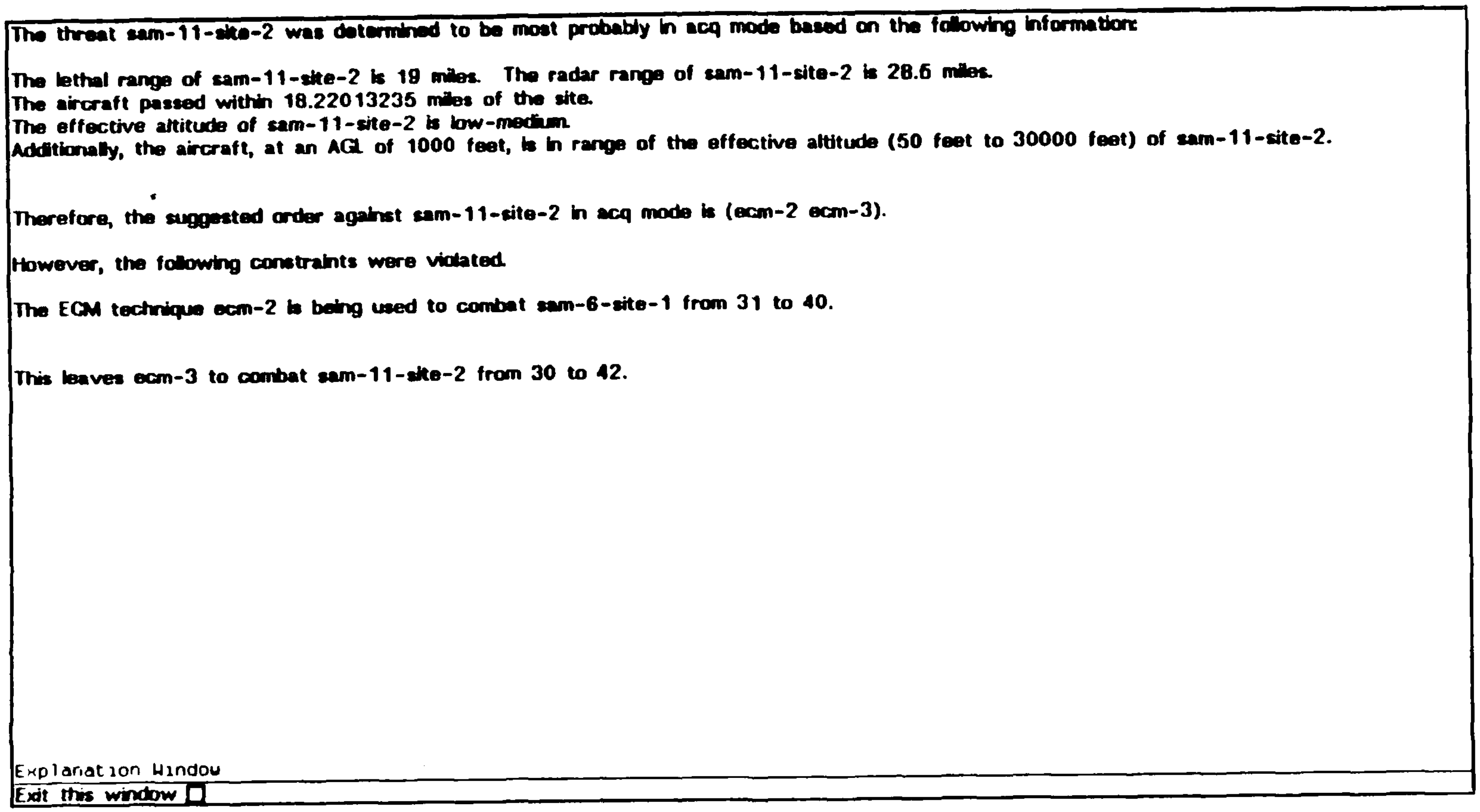


Figure 17. A Search Explanation

names of the lists on the left-hand side of the window are a combination of the mode of the threat and whether the aircraft is above, in, or below the effective altitude of the threat. To change a value in this window, the user should place the mouse pointer on a value and click left. The user should now enter a new value in the form of a list. If a list is not entered, the system does not accept the input and the user is allowed to change his input. After all alterations are made, the user should click on the "Do it" box. This updates the knowledge base.

Two more facilities are provided by the "Change Threat ECM Order" option of the search window. The first facility is the ability to load a new ECM techniques file into the system. The default ECM techniques file was loaded automatically immediately after the threat file was loaded. Selecting "Read New ECM Techniques from File" allows the user to specify a file containing new ECM techniques. This file is loaded into the system thereby updating the knowledge base. The second facility is just the opposite of the first. This facility allows the user to save new ECM techniques to a user-selectable file. This is done by selecting "Save the Current ECM Techniques to File" from the "Change Threat ECM Order" menu.

After the user is satisfied with the results of the search, he should go to the map window using the "Change Screen" option of the search window. The user is now ready to simulate the recommended ECM strategy.

The user should select either "Run Simulation" or "Step Simulation" from the simulation menu. "Run Simulation" is recommended. "Step Simulation" may be used to increment the simulation one tick for each time the user clicks the mouse. Either operation activates the simulation. First, a simulation trace file is initialized. This will require about a few seconds to complete. After the file is initialized, the simulation begins. An airplane icon is 'flown' along the mission route applying the recommended ECM strategy. The current speed, AGL, and simulation tick can be seen in the map information window at the right of the map. The simulation may be stopped by clicking the right mouse button. To start the simulation again, the user should select either "Step Simulation" or "Run Simulation" from the simulation menu. Once the simulation is complete (the airplane returns to home base), the simulation window is exposed and the simulation results are displayed.

Simulation Window

The simulation window is used to display the simulation results and the simulation trace. This window is also scrollable thereby allowing the user to view all simulation

information. Figure 18 illustrates a simulation result. The first column represents the threat. The second column displays the most probable mode of the threat. The third column gives the ECM applied to the threat during the simulation. Finally, the last column displays the effectiveness of the ECM technique against the threat.

If the user wishes to obtain an explanation of how the effectiveness was derived, he has two options. Both options require the user to select the ECM technique in question. This is done by placing the mouse pointer over the technique. This causes the line to become boxed. Now the user can either click left for an explanation given using text (See Figure 19) or he can click the middle button to obtain an explanation using an inference network (See Figure 20). Both explanations provide the same information. To exit either explanation, select the "Exit this window" option.

Using the "Simulation Window Operations" the user can view the simulation trace by selecting "View Simulation Trace". The user can also obtain a hard copy of the simulation results and trace by selecting the appropriate item. The simulation results may be displayed by selecting "Display Simulation Results".

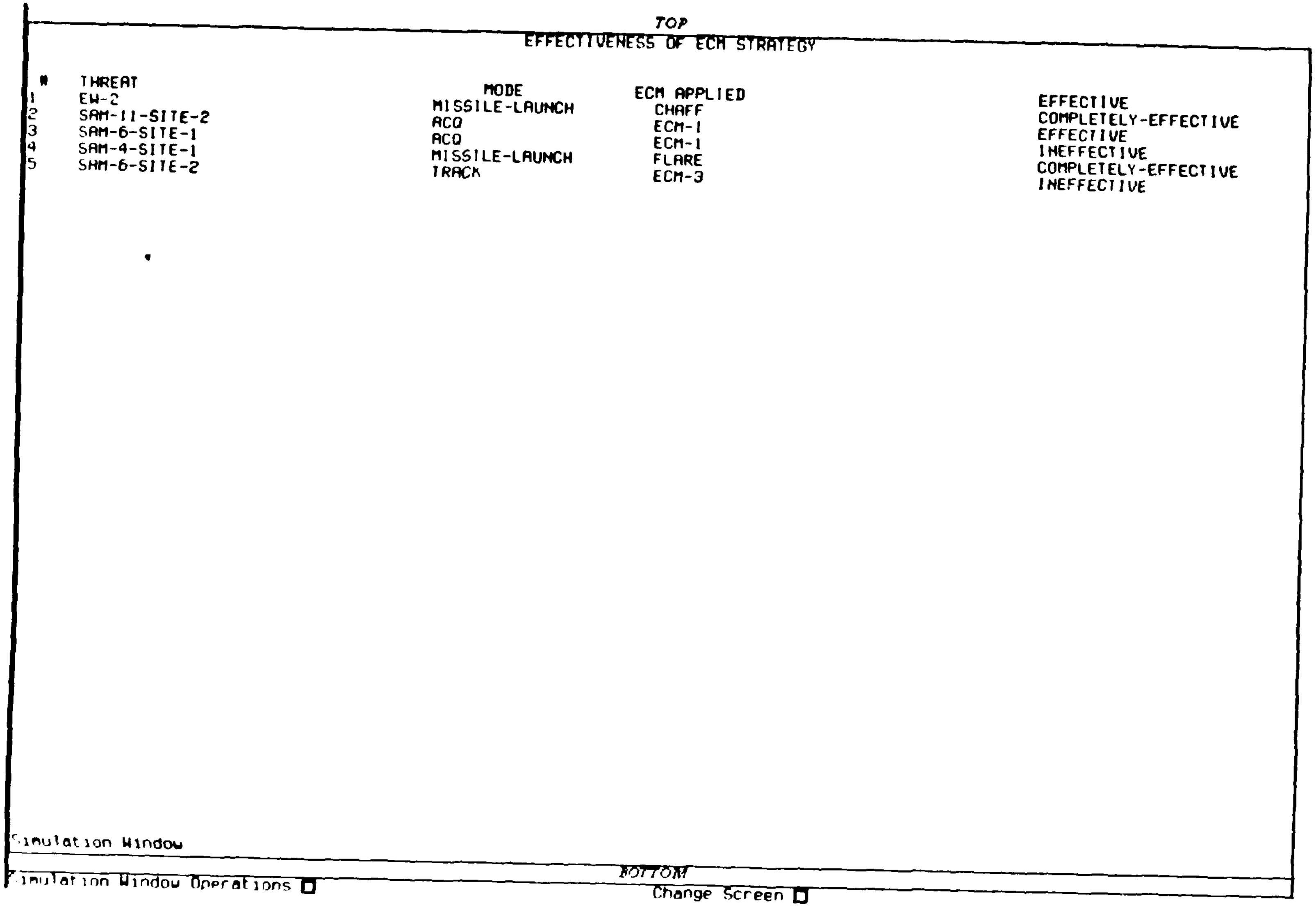


Figure 18. A Simulation Result

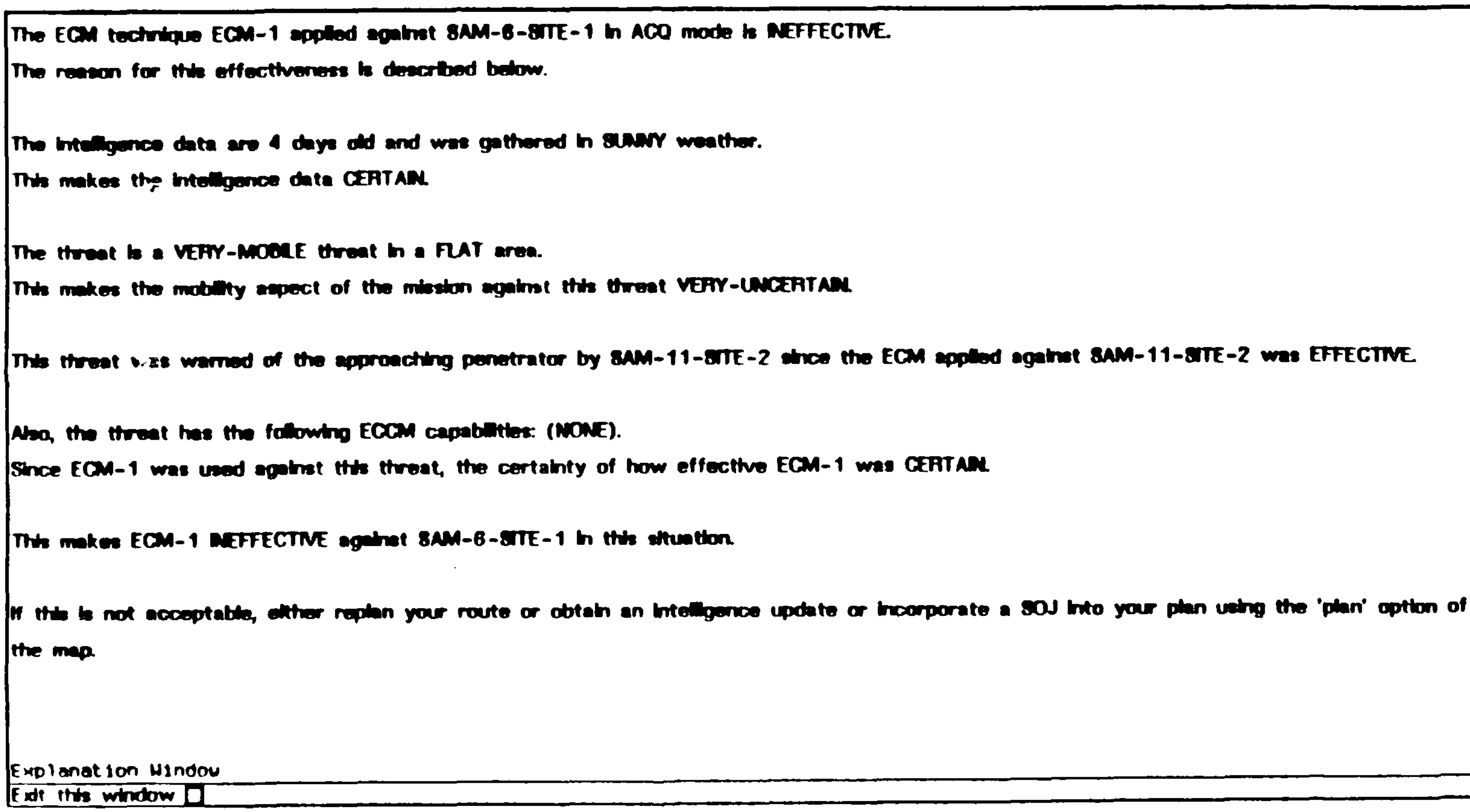


Figure 19. A Simulation Explanation Using Text

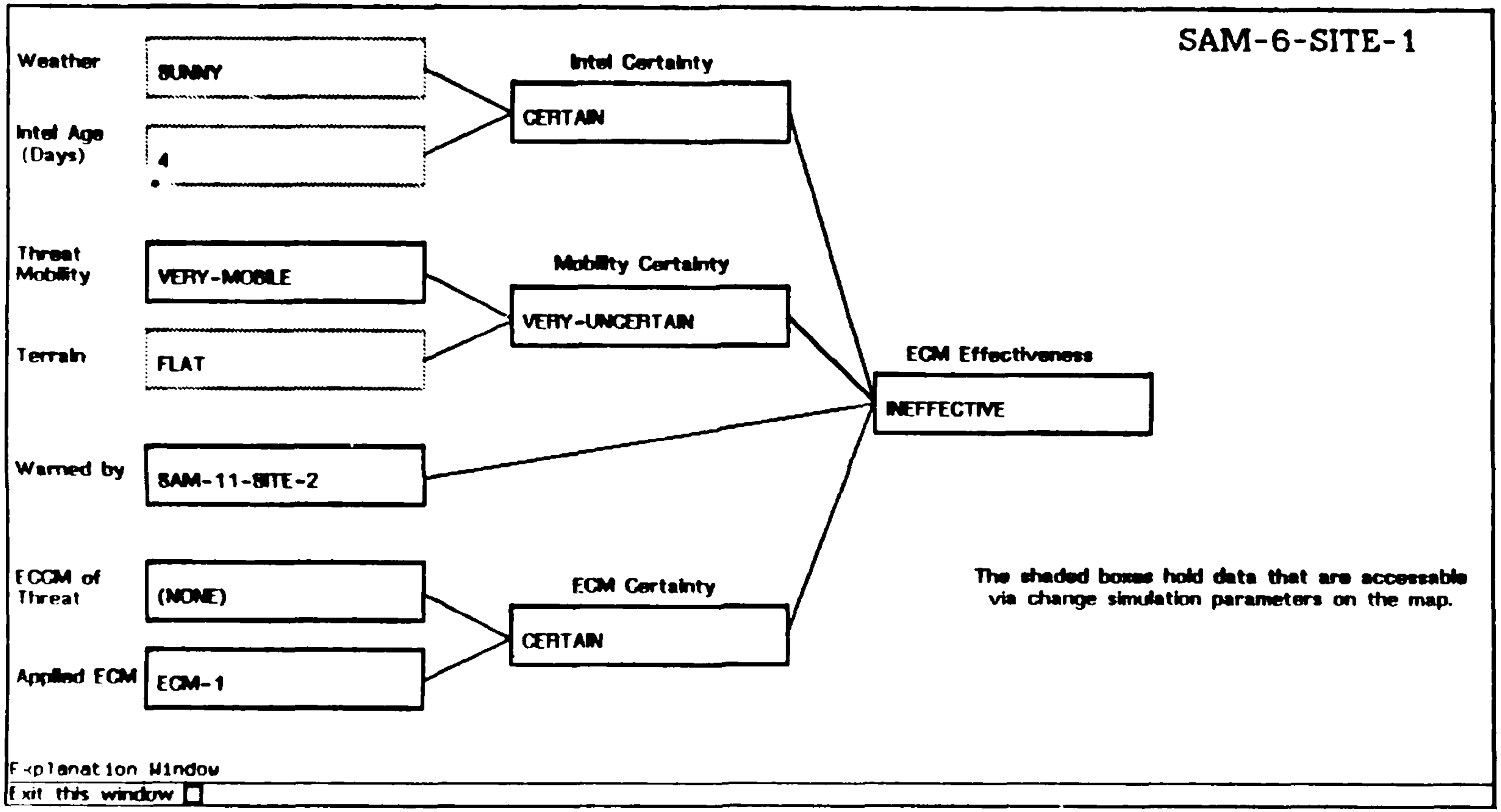


Figure 20. A Simulation Explanation Using an Inference Network

Stores Management System

The Stores Management System (SMS) allows the user to change the configuration of the aircraft's stores. Figure 21 illustrates the SMS. By selecting configurations from the "Standard SCL" option or the "From Dash-1" option, the user can select the configuration of the aircraft's stores. The user may also change individual stations on the aircraft. This is done using the "Change Stations" option. The user is guided through a series of windows to change the configuration of a station. The on-board expendables may be altered using the "Change On-Board" option. Selecting this option allows the user to change the number of expendables aboard the aircraft using a window.

Shutting Down the Planner

The planner should be shutdown by first pressing the "Select" key and then the "L" key. This places the user in a Lisp Listener. The user should then type "(bye)". The system will respond with a question. The user should answer with "y". This shuts the Explorer system down.

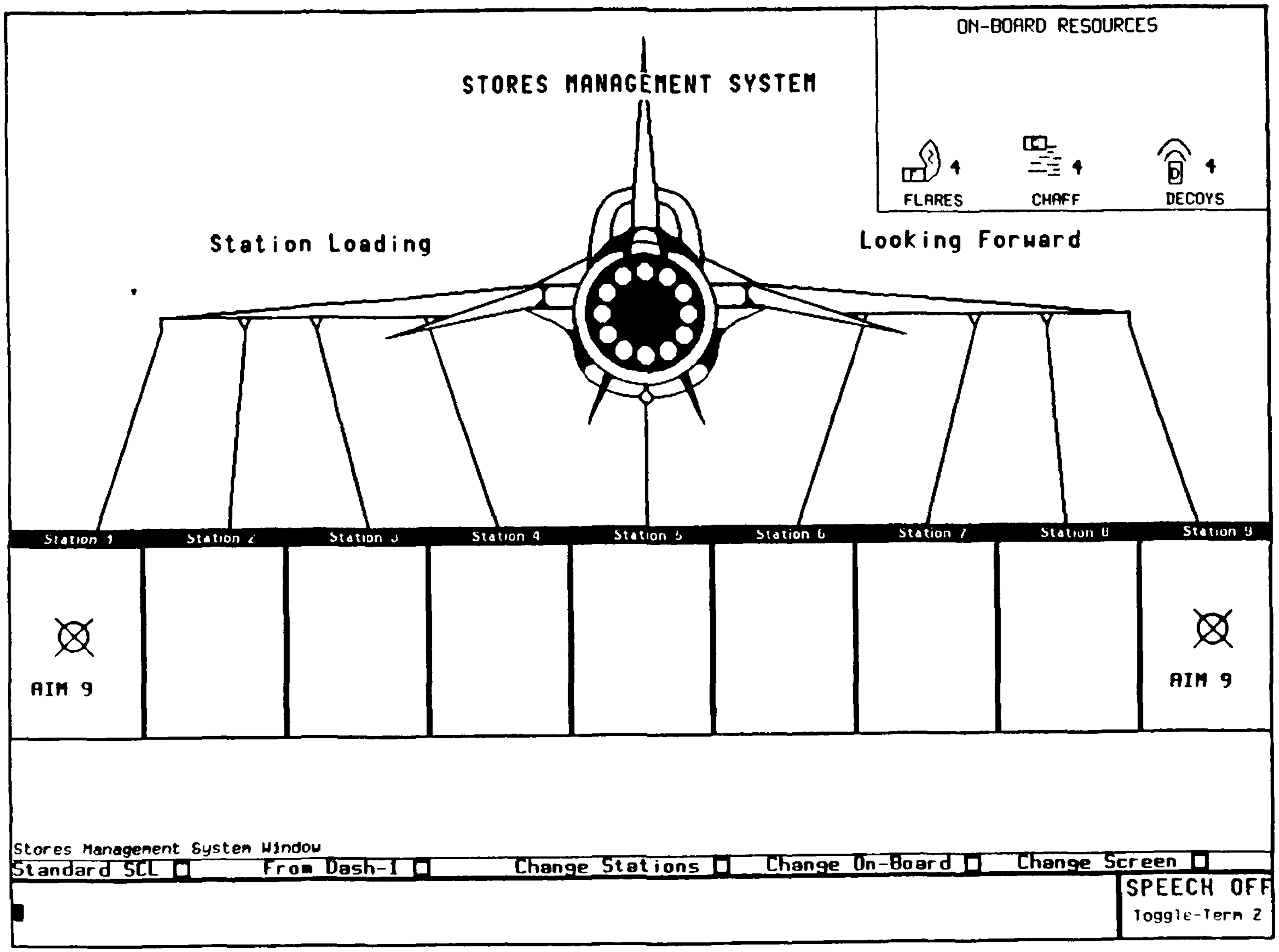


Figure 21. Stores Management System

Appendix C: Electronic Warfare

The following sections discuss the three fundamental components of electronic warfare. As discussed in chapter II, the three components are electronic warfare support measures, electronic countermeasures, and electronic counter-countermeasures. The significance of radar in the field of electronic warfare concludes the discussion.

Electronic Warfare Support Measures (ESM)

Dr. Schleher describes ESM as follows:

> ESM is that division of EW involving actions taken to search for, intercept, locate, and immediately identify radiated electromagnetic energy for the purposes of immediate threat recognition and the tactical employment of forces (Schleher, 1986:6).

This definition is based on the definition provided by the Joint Chiefs of Staff and is generally accepted by the electronic warfare community.

The primary function of ESM is to provide intelligence information about the hostile air defense systems to the crew of a tactical aircraft penetrating the hostile forces. This intelligence information might include the number and location of the different threats, the strategy used in the employment of the threats, and the capabilities of the threats. This information is obtained by "intercepting, identifying, analyzing, and locating sources of hostile radiation" (Schleher, 1986:6). The intelligence gathered

during these operations underlie the components of electronic warfare and are essential to the effective use of the same (Fitts, 1980:36). For example, information gained during a penetration is extremely valuable to aircrews scheduled to penetrate the same area. This is a tremendous advantage of using ESM; however, it is no the only advantage.

ESM have other advantages that make it a desirable asset on tactical aircraft. One of these advantages of ESM is that it operates in a completely passive mode. It does not radiate electromagnetic energy and as such does not provide hostile defense systems with a signal to home in on. Another advantage is ESM is capable of detecting threats before the threat is capable of detecting the aircraft (Schleher, 1986:8).

Since ESM reacts to radiated electromagnetic energy, a good defense for the ESM systems is to limit the number of emissions from a threat site until necessary (Schleher, 1986:8). This operating concept is in concert with the Soviet doctrine. Soviet doctrine dictates the use of emission control (EMCON) (Correll, 1987:65). EMCON is preventing the transmission of electromagnetic signals that may be detected by a penetrating aircraft until the site is discovered or the communication is reasoned to be vital to survival.

ESM is characterized by its need for the immediate gathering of information in support of a tactical mission. The information is required immediately in order to make time-critical decisions.

Radar Warning Receiver. The radar warning receiver (RWR) is the system used to obtain this timely information. The RWR has also been known as radar homing and warning (RHAW) (Fitts, 1980). The author prefers the RWR term and will use it throughout the remainder of the thesis.

The RWR is an example of an ESM system and "intercepts radar signals and analyzes their relative threat in real time" (Schleher, 1986:6). The primary goal of the RWR is to warn the crew of a potential attack on the aircraft by a threat. The RWR first intercepts the radar signals and stores the signal parameters such as frequency, pulsewidth, amplitude, and other parameters. Once the parameters are stored, the RWR sorts the threats into categories based on the parameter information and then performs a match of the stored information to a set of radar signatures stored in a library. This matching process culminates in the threat identity which in turn is used to prioritize the list of threats (Schleher, 1986:47). This list of prioritized threats is displayed to the crew in the form of a threat display on a small screen. The information displayed includes the type and location of the threat relative to the

aircraft and is used to determine the evasive action (if any) needed to avoid the threat.

Real Time Processing Considerations. The real time processing of the gathered information is becoming increasingly difficult. This difficulty stems from the extremely dense and sophisticated radar systems supporting the hostile threats (Correll, 1987:64; Schleher, 1986:337). Additionally, the fusion of the various sensors aboard the aircraft creates problems against this dense environment. The different sensors provide valuable information for the pilot. However, the data obtained from these sensors must be integrated into information the pilot can reason with. The pilot cannot conceivably integrate the data; the task is simply too overwhelming. Another cause of the difficulty in real time processing is today's RWR systems not only must warn of a radar system painting the aircraft but also must contend with millimeter-wave and laser warning functions (Hartman, 1987:23-24). The real time processing requirements coupled with the dense threat environment obviously prevent the pilot from performing the RWR functions. Thus, the RWR is automated.

Electronic Countermeasures (ECM)

"ECM is defined as actions taken to prevent or reduce the enemy's effective use of the electromagnetic spectrum" (Schleher, 1986:9). This definition was first formalized by

the Joint Chiefs of Staff and is generally accepted by the electronic warfare community.

As this definition implies the primary objective of ECM is to confuse the enemy in such a way to allow penetrating aircraft to complete their mission successfully. In other words, ECM is primarily a defensive technique used for protection (Fitts, 1980:88). The underlying principle of ECM is to prevent the enemy from obtaining the information he deems pertinent. This, in effect, increases the uncertainty of properly identifying the aircraft by the air defense system.

Confusing the enemy defenses is commonly accomplished by introducing electromagnetic signals into the enemy's radar systems. These signals prevent the system from performing its mission by altering the enemy's radar parameters. Alteration is commonly accomplished by either surrounding his radar return with sufficient amounts of false data that the actual return is not detectable or swamping the enemy's radar system with a great quantity of false or noisy data (Schleher, 1986:10).

<u>ECM by Jamming and Deception.</u> ECM includes jamming and deception. These two categories serve to confuse the enemy. Although jamming and deception seem to be the same, the true distinction is the intended results.

Noise Jamming. Jamming has been defined differently by several authors (Schleher, 1986:9; Fitts, 1980:2; Van Brunt, 1978:85; Chizum, 1985:98-100). However, the definition used in this thesis was based on a combination of Fitts' and Schleher's definitions. Jamming is best described by deliberately radiating or reflecting electromagnetic energy with the intent to undermine the enemy's use of electronic systems. Jamming is concerned with swamping an enemy's defense system with electromagnetic energy such that the system is not able to extract the true data. This increases the noise level in the radar receiver making the detectability of an aircraft more difficult. Consequently, this form of ECM is best implemented using random or noise-like signals (Fitts, 1980:83). This form of jamming is referred to as noise jamming throughout the remainder of the thesis to distinguish it from deception jamming.

Noise jamming is the most common form of ECM and is performed in two basic modes -- spot and barrage (Schleher, 1986:10; Fitts, 1980:89-91). Figure 22 illustrates the two jamming techniques.

Spot jamming focuses the jamming power into a narrow bandwidth. This technique is only effective if the frequency parameters of the hostile radar site are known. Thus, spot jamming is typically used to combat a specific radar (Fitts, 1980:89) and is the most effective against

radars in which the frequency agility is slow. Frequency agility is the ability of a radar to change its operating frequency to counter spot jamming (Fitts, 1980:91). The nature of spot jamming implies that the jammer must be tuned to the same frequency as the hostile radar. This requires the pilot's or electronic warfare officer's attention thereby degrading situational awareness. This is discussed in chapter II in the section titled 'Situational Awareness'.

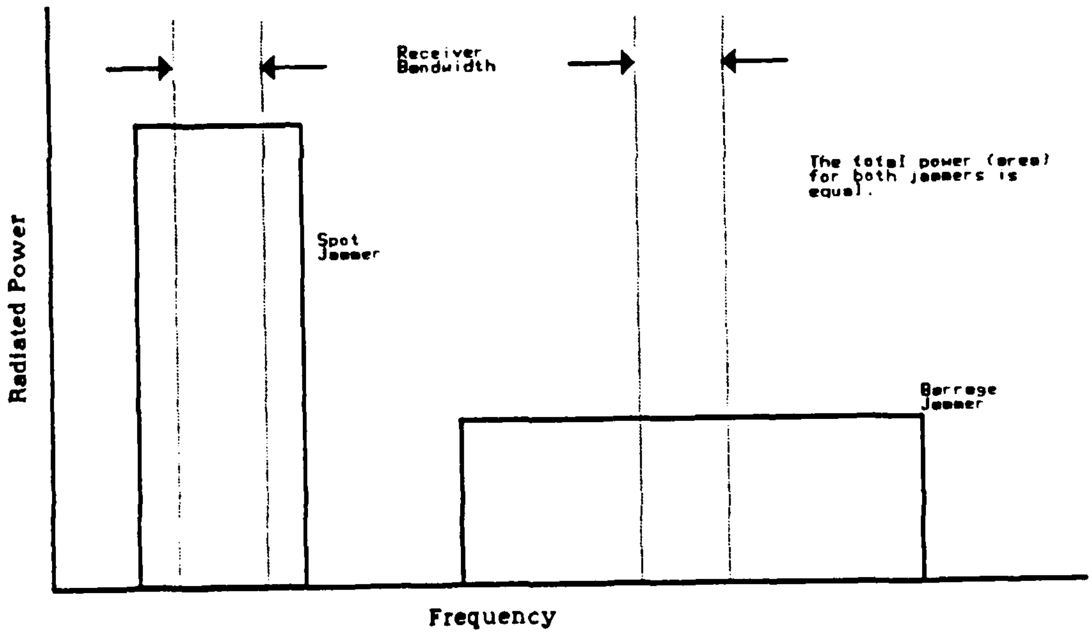


Figure 22. Receiver Bandwidth and Jammer Spectral Power Density
Source: (Fitts, 1980:90)

In order to overcome the constraint of having a slow frequency agility or uncertain frequency parameters, barrage jamming may be used. Barrage jamming spreads the jamming power over a greater bandwidth than spot jamming and is more effective against radars that have fast frequency agility. This results in two major consequences. First, the hostile radar frequency has a greater probability of being jammed. The second consequence is that the power of the jamming signal actually jamming the radar is less than spot jamming.

A barrage jammer requires considerably more effective radiated power (ERP) than a spot jammer for the same jamming effectiveness (Schleher, 1986:10). This phenomena is illustrated in Figure 22. The power distribution of the two techniques is the result of having limited jamming power on-board the penetrating aircraft.

Size and weight constraints of the aircraft dictate the power limitation (Fitts, 1980:115). Aircraft typically cannot carry a sufficient number of jammers to jam all threats (Schleher, 1986:13). Consequently, the air defense doctrine of the Soviet Union is to practice the concept of frequency diversification in which the radar systems uses several frequencies on a wide bandwidth (Schleher, 1986:337). This forces the penetrating aircraft to either carry a wide variety of spot jammers or to spread the barrage jamming power to accommodate the wide swing in frequencies (Fitts, 1980:91). However, as mentioned, the

aircraft must operate within the size and weight constraints. A solution to this dilemma is to provide another aircraft for the sole purpose of providing ECM support.

Deception. Deception, on the other hand, is defined quite well by Schleher:

> Deception is the deliberate radiation, reradiation, alteration, absorption, or reflection of electromagnetic energy in a manner intended to mislead a hostile force in the interpretation or use of information received by his electronic systems (Schleher, 1986:9-10).

The objective of deception is to provide the enemy with false, yet realistic, information by altering the radar returns of the hostile systems. Altering the returns commonly causes the hostile radar site to interpret the radar data incorrectly. Thus, the radar site will not have a clear picture of the situation. The deception technique mimics the radar echo of a bogus aircraft. Deception is interested in injecting quality signals into the frequency spectrum of interest. The injection of signals causes the information rate at the radar site to increase consequently increasing the number of potential mistakes by radar personnel or by overloading the signal processing capability of the site equipment (Fitts, 1980:82-83). This is different from noise jamming in that noise jamming tries to overwhelm the radar systems with noise making the extraction of the real data difficult. Deception is accomplished using

deception jammers and is referred to as deception jamming throughout the remainder of the thesis for clarity.

The primary reason for using deception jamming is because noise jamming is not an appropriate technique for tracking radars (Schleher, 1986:138). Noise jamming can only jam ranging information and not angle information. The tracking radar will still know the angle of the aircraft. However, some missile guidance systems are capable of operating with angle information only. This forces the aircraft to employ a different form of ECM -- deception jamming.

The objective of deception jamming is to deny the tracking radar angle and range information. This allows the aircraft to break the track of the tracking radar system. Once track is broken the radar must be operated manually in order to reacquire the aircraft since the radar is no longer receiving tracking information. This manual operation is time consuming and may give the pilot enough time to elude the radar.

A significant advantage of deception jamming over noise jamming is that of power consumption. Since deception jamming operates synchronously with the tracking radar, the amount of power expended is significantly less than noise jamming. The waveform generated by the deception jammer is matched with the radar's waveform. In other words, the jammer operates at a duty cycle equal to that of the

tracking radar. This minimizes the power requirements of the aircraft and synergically allows the jammer to effectively jam multiply threats (Schleher, 1986:138).

The techniques used for the deception are characterized into three categories: range gate deception, angle deception, and velocity deception. These techniques employ the same basic concept; the radar echo of the aircraft is shifted slightly by the aircraft. Subtle differences do exist between the three techniques. However, these differences are not significant for the purposes of this thesis. Figure 23 illustrates a form of deception jamming called range gate pull-off (RGPO).

Tracking radars use tracking gates to provide an envelope for the radar echo. The gates are adjusted by the tracking system by anticipating the future position of the aircraft. The signal processing of the radar is concentrated within these gates; other returns are ignored. The objective of deception jamming is to steal the gate by forcing the gate to a position other than the true echo. This is accomplished by generating a cover pulse signal using a jammer that is noticeable stronger than the actual aircraft echo. This bogus echo will initially be centered with the actual aircraft return. However, as time progresses the jammer shifts the stronger echo in time. Consequently, the radar system shifts the gate to follow the stronger signal thereby corrupting the true tracking

information. Once the gate is completely stolen, the deception jammer may either be turned off causing the aircraft to disappear from the tracking system or allowed to move the gate around the spectrum causing the radar to waste its time following a false aircraft. In either case, the tracking errors are sufficient enough to cause substantial errors in weapon guidance.

Expendable Electronic Countermeasures. Expendable electronic countermeasures are resources deployed off-board the aircraft. These resources are, as the name implies, deployed once and are effective for a limited time span. Expendables are divided into two categories. The first category is passive expendables and includes chaff and flares. The second category includes the active expendables such as miniature jammers and anti-radiation missiles (ARM).

Chaff is by far the oldest radar countermeasure (Schleher, 1986:183) and is a collection of narrow strips of aluminum foil or glass fibers coated with a metallic substance. These strips of reflective material are packaged in units such that deployment is simple. Once deployed, the units burst open and fill the atmosphere with chaff. The purpose of chaff is to confuse the hostile radar by reflecting radar signals in order to provide the radar system with false information. The effectiveness of chaff depends on the current situation and its intended use. A discussion of chaff is beyond the scope of this thesis.

RGPO

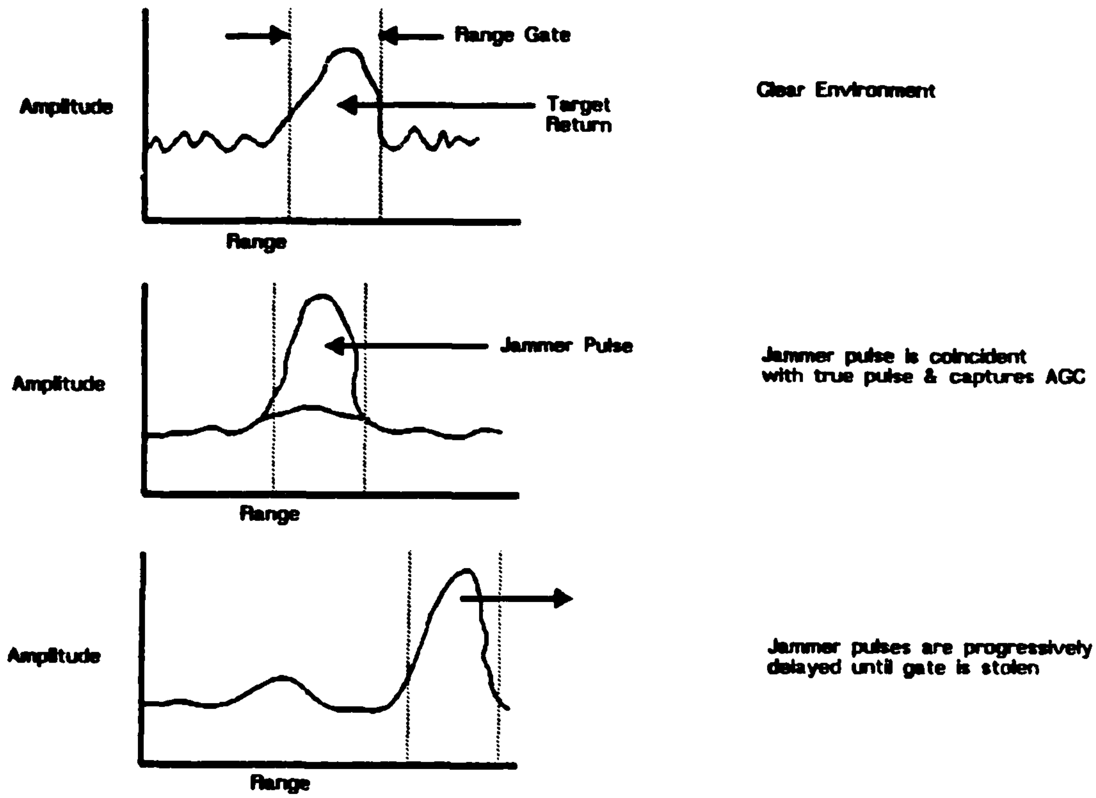


Figure 23. Range Gate Pull-Off
Source: (The Johns Hopkins University, 1986:1-99)

Flares are another form of passive expendable countermeasure. Flares are typically used to counter infrared (IR) seeking missiles (Schleher, 1986:178). Flares, of course, produce tremendous amounts of heat. Since IR seeking missiles home in on heat, an effective countermeasure for avoiding it is to deploy a flare as the missile is homing in on the aircraft. The flare captures

the missiles tracking system causing the missile to follow the flare instead of the aircraft (Schleher, 1986:178).

The next form of countermeasure is active miniature jammers (decoys). These jammers are similar to the on-board jammers. However, the expendable jammers have a limited power output. This affects the deployment strategy of these miniature jammers. The primary objective of using expendable active countermeasures is to inundate the enemy's radar system by placing a large number of jammers in the vicinity of the defense systems (Fitts, 1980:102; Schleher, 1986:178-180). The jammers overload the signal processing capabilities of the radar system.

The last form of expendable countermeasures is the ARM. These missiles are one of the most serious threats to the radar systems (Schleher, 1986:18). ARMs use passive tracking seekers to home in on the radar's emissions (Schleher, 1986:18-19) and are typically launched from Wild Weasel aircraft.

Resource Management. Since tactical aircraft have limited on-board power and expendables, these resources must be deployed in an optimal manner in order to make best use of the imposed constraints. On-board power and expendable resources are collectively called resources in this thesis. Resource management is a serious and challenging consideration for the ECM design engineer as well as the pilot (Geiger, 1987; Schleher, 1986:135). Since the threat

environment is so dense, the EW resources may be taxed beyond their capabilities. For example, a specific jammer may be required to jam two threats operating on different frequency bands at the same time. Additionally, the number of expendable resources is fixed at takeoff. These resources must be capable of being scheduled such that the threats are countered, the jamming signals do not interfere with other on-board equipment such as the RWR, and the power and number constraints of the aircraft are not violated.

ECM Missions. As mentioned earlier, the penetrating aircraft is constrained by size and weight limitations of the aircraft. These limitations force the pilot to make serious decisions about how much ECM equipment to carry while sacrificing potentially valuable assets such as extra fuel or more munitions. This gives rise to a new form of ECM -- support ECM. In fact, four basic missions of this type are currently categorized. These missions are stand-off ECM, escort ECM, self-protection ECM, and mutual support ECM (Schleher, 1986:11).

Stand-off ECM is commonly called stand-off jamming and is performed by a stand-off jammer (SOJ). SOJ provide jamming support for the penetrating aircraft. The SOJ typically operates outside the hostile areas of the enemy defenses because of its general lack of defensive weapons. In fact, the SOJ spends the majority of its time behind the forward edge of the battle area (FEBA). The SOJ carry

substantially more ECM equipment than the penetrating aircraft. Since the SOJ operates outside the threat environment, it is farther away from the threats to be jammed. This extra distance dictates the need for additional jamming power to compensate for the added distance. The extra jamming power may be in the form of more jammers or larger, more powerful jammers.

The second type of ECM mission is the escort ECM. Escort ECM is used when the penetrating aircraft is not capable of carrying all ECM resources required for safe penetration. Escort ECM places the jamming responsibility upon the escort aircraft. The escort aircraft, as the name implies, escorts the penetrator to the target. Of course, now the escort jammer is vulnerable to attack by the defense systems. In fact, the escort jammer is typically a high priority target since its destruction will leave the penetrator with little or no ECM protection (Schleher, 1986:13,110; Fitts, 1980:87). The real advantage of escort ECM lies in the fact that the jammer is closer to the threats and as such requires less power than a SOJ (Schleher, 1986:13).

The next type of ECM mission is the self-protection ECM mission. This form of ECM is characterized by the fact that the penetrating aircraft carries all the ECM equipment required to safely complete the mission. The aircraft must

provide its own protection. Self-protection ECM is generally used when a single aircraft is the penetrator.

The last form of ECM mission is the mutual support ECM mission. Mutual support missions have more than one penetrating aircraft each carrying ECM equipment. The real power of this type of mission is the ability to coordinate the ECM of the different aircraft. Another advantage is the larger effective radiated power (ERP) (Schleher, 1986:13).

Pilot Intervention. The obvious question is who performs all of these electronic countermeasures. The pilot commands the ECM equipment on his aircraft thereby forcing him to dedicate attention away from the primary task of flying the aircraft. He must be able to not only elude the hostile air-defense systems but also outwit them. This places a substantial burden on the pilot to successfully perform all of these tasks synergically. This dilemma is discussed in greater detail later in the thesis in the section dealing with situational awareness.

Electronic Counter-Countermeasures (ECCM)

Several definitions for ECCM are available. This thesis will use the following definition. ECCM is "actions taken to insure friendly effective use of the electromagnetic spectrum despite the enemy's use of EW" (Fitts, 1980:2). This definition was derived from the JCS Memorandum of Policy 95 and is widely accepted.

As the definition implies, ECCM is typically the reaction of the ground-based radar sites to the penetrating aircraft's use of ECM. As such, ECCM is the result of performing improvements to the radar system. These improvements are required to correct or compensate for a design weakness discovered and exploited by the ECM of the aircraft (Schleher, 1986:19). This brings about an interesting point of ECM and ECCM. The designers of these systems must be completely versed in the enemy's designs and inadequacies. The designers must also realize that any improvement or new technique will soon be countered Schleher, 1986:19). This is one of the reasons why electronic warfare is such a dynamic field.

ECCM is best characterized by the fact that it is concerned with the actual design of the equipment used in EW. Since the primary equipment used in ECCM is the radar, radar design is the primary consideration for an effective ECCM system. The radars used in ECCM are designed to be able to combat the ECM of a penetrating aircraft by manipulating the parameters of the radar system. Some of these parameters include power, frequency, and pulse length. Since the ECCM capabilities of a radar system are relatively fixed during the design of the system (Fitts, 1980:115), the true ECCM capabilities of a radar system depend heavily on the design of the system. However, a discussion of radar design is beyond the scope of this thesis. Therefore, ECCM

is not discussed as thoroughly as the other two divisions of EW. The reader will not suffer for the absence of this information. The interested reader is referred to the books by Johnson (Johnson, 1979) and Schleher (Schleher, 1986:199-309) for an excellent overview of some of the design principles used in the radar systems to provide effective ECCM.

Radar Networking. Another consideration for an effective ECCM system is that of networking the radars (Fitts, 1980:124). This is the typical configuration of an air defense system. The networking of the radars provides some interesting ECCM characteristics to the system. The first ECCM characteristic provided by networking the radars is frequency diversification. This concept was discussed earlier in the ECM section. Frequency diversification simply means spreading the operating frequencies of the radar sites over a large spectrum. As mentioned earlier, this creates a serious problem for the ECM systems of the aircraft. The ECM system may not be able to jam all of the frequencies at once.

Another advantage of a network of radars is the capability to perform triangulation (Fitts, 1980:124). The radars may be capable of locating the aircraft based on angular information only. This is useful when the aircraft is denying all radar sites ranging information by incorporating RGPO for example.

The networking of radars is not without serious problems. The major problem confronting these systems is the inherent information processing capabilities. The data rates required for radar networks is a serious limiting factor in the actual implementation. The rates typically exceed the processing capabilities of the system. This is the primary reason for incorporating a human operator in the system.

Operator Intervention. Regardless of how well the radar system is designed, a well-designed radar system is by no means the panacea for ECCM. The equipment must be used properly in order to effectively combat ECM and control the data rates of the radar systems. The heuristics used by the human operators are essential to controlling the data rates of the radar network (Fitts, 1980:126). This implies that the operators must be prepared for the ECCM challenge. Thus, ECCM is also concerned with the training of the equipment operators (Fitts, 1980:115). The operators must be able to manipulate the equipment such that the ECM of the aircraft is countered.

The Use of Radar for EW

The JCS definition of EW clearly specifies the goal of electronic warfare is to control the electromagnetic spectrum or, more specifically, control the sensors used to radiate the electromagnetic energy used for electronic

warfare. The sensor most commonly used for the exploitation of the electromagnetic spectrum is the radar (Fitts, 1980:7; Schleher, 1986:200). This fact is reiterated by the following excerpt:

> Soviet Union is making substantial progress in developing and deploying military radar as an essential corollary of its emergence as a world-wide military power.
> The Russians apparently have embraced the new maxim that he who controls the electromagnetic spectrum controls the outcome of any conflict in modern war or global politics. They understand and appreciate the essential role radar plays in fulfilling this dictum (Miller, 1971:14).

Major August Golden stated the basic function of a radar is "to either detect the presence of a target or to determine the location of a target" (Golden, 1982:11).

Locating a penetrating aircraft is one of the first objectives of an air defense system. Without the location of the aircraft, the air defense system would not be able to perform its task well if at all. Radar is the eyes of the defense system and is essential to any electronic warfare operation.

Penetrating aircraft are typically equipped with radar warning receivers (RWR) to detect the presence of a hostile radar site. The RWR provides the pilot of the aircraft a warning that a radar is illuminating his aircraft. Radar principles are used in detecting the illuminating signals.

Since radar is employed in a large number of modern air defense systems (Fitts, 1980:35), aircraft trying to penetrate these defenses must be able to suppress the enemies ability to use radar effectively consequently increasing the probability of a successful mission. Clearly, the penetrating aircraft should be equipped with devices capable of performing electronic countermeasures (ECM) to combat these threats that employ electromagnetic measures for acquisition or tracking of targets.

Electronic counter-countermeasures are also implemented using radar. In fact, ECCM is almost exclusively related to radar and its design. The effective design of radar systems underlies the concept of ECCM. Radar is paramount when considering ECCM.

Summary

Electronic warfare is an extremely complex domain. This appendix attempts to describe this domain. This appendix has presented an overview of the various electronic warfare components and how these components relate to each other. Additionally, the importance of resource management and the use of radar were also discussed.

Appendix D: Requirements Matrix

The following matrix outlines the requirements the researcher considered during the development of the planning system. However, not all requirements are implemented in this research. Chapter IV discusses these requirements by giving a definition of requirement and whether it was implemented.

This matrix presents the requirements as well as how the system developed during this research effort (hereafter referred to as prototype) satisfied the requirement and how an operationally useful system (OUS) could handle the requirement. The first line after the requirement description is how the prototype satisfied the requirement, if at all; the second line is how an operationally useful system could satisfy the requirement. The matrix is shown below.

1. Define the simulation environment.

    a. Create egress and ingress routes.

        Prototype: Enhanced TMP.

        OUS: Enhanced TMP.

    b. Provide ECM techniques against threats.

        Prototype: MU knowledge base and SMS.

        OUS: Select from detail Air Force arsenal description of EW equipment.

c. Create threat environment.

Prototype: Enhanced TMP.

OUS: Generated by intelligence office.

d. Create strike package.

Prototype: Enhanced TMP.

OUS: Specified by the planning team.

e. Create/access a terrain map.

Prototype: TMP.

OUS: Select from DMA library of maps.

f. Load pilot preferences.

Prototype: Pilot enters preferences into the ECM generation module.

OUS: Each pilot creates a preference data tape to be loaded each time the pilot uses the system.

g. Load current Soviet doctrine.

Prototype: Use strategies gleaned from open literature and implement using MU.

OUS: Doctrine generated by FTD.

2. Modify simulation environment.

a. Modify route.

Prototype: Enhanced TMP.

OUS: Enhanced TMP.

b. Modify ECM strategies.

Prototype: Strategy acquisition module in search.

OUS: Supplied by EW engineer.

c. Modify threat environment.

Prototype: Enhanced TMP.

OUS: Enhanced TMP.

3. Perform simulation.

a. Time-driven.

Prototype: Simulation module.

OUS: ROSS.

b. Event-driven.

Prototype: Not implemented.

OUS: ROSS.

c. Allow objects to interact.

Prototype: MU knowledge base.

OUS: ROSS.

4. Simulation features.

a. Display threats or danger indices.

Prototype: Not implemented.

OUS: Use array processor to generate a dynamic threat map.

b. Terrain masking.

Prototype: Not implemented.

OUS: Use algorithm similar to RPA.

c. Output traces.

Prototype: Simulation interactions are saved to a file for future reference.

OUS: ROSS.

d. SAM/AAA fly out.

Prototype: Not implemented.

OUS: Incorporate simulation for fly out (end game).

e. Probabilistic radar acquisitions.

Prototype: Intelligence gathering mission.

OUS: Use a more realistic model of the probability of acquisition.

f. Multiply levels of ECM equipment representation.

Prototype: Generic, top-level ECM representation.

OUS: Use classified data.

5. Planning features.

a. Expert system plans route for pilot.

Prototype: Not implemented.

OUS: RPA-type implementation.

b. Expert system plans ECM strategies.

Prototype: Constraint-directed search.

OUS: Constraint-directed search coupled with an expert system.

6. Critique features.

a. Evaluate route.

Prototype: Not implemented.

OUS: RPA-type implementation.

b. Evaluate ECM strategies.

Prototype: Knowledge-based simulation.

OUS: Knowledge-based simulation.

7. Man-Machine interface.

a. Graphics displayed.

1. Threats.

Prototype: Enhanced TMP.

OUS: Enhanced TMP.

2. Target.

Prototype: Enhanced TMP.

OUS: Enhanced TMP.

3. Home base.

Prototype: Enhanced TMP.

OUS: Enhanced TMP.

4. IP, waypoints.

Prototype: Enhanced TMP.

OUS: Enhanced TMP.

5. Wild weasels (SOJ).

Prototype: Enhanced TMP.

OUS: Allow SOJ mobility.

6. FEBA.

Prototype: Enhanced TMP.

OUS: Allow a more dynamic FEBA.

7. A/C ECM equipment.

Prototype: Enhanced SMS.

OUS: Enhanced SMS.

b. Speech output.

Prototype: Enhanced TMP.

OUS: Enhanced TMP.

c. Pilot input.

1. Mouse.

Prototype: Enhanced TMP.

OUS: Enhanced TMP.

2. Keyboard.

Prototype: Enhanced TMP.

OUS: Enhanced TMP.

d. Present options in a logical sequence.

Prototype: Display only germane options at any one time during the planning process.

OUS: Display only germane options at any one time during the planning process.

Appendix E: Tactical Mission Planning

The Tactical Fighter Environment

The tactical missions of today are characterized by using low altitude to increase the probability of a successful mission (Miller, 1983:1-1). The pilots are being forced to an astonishing low altitude during a tactical penetration. Capt Milt Miller best described this dilemma by stating

> pilots routinely employ their aircraft within 50-100 feet of the ground at 500 knots while maneuvering in excess of 5 Gs attempting to accomplish a variety of tasks inside and outside of the cockpit (Miller, 1983:1-1).

Three basic reasons exist that cause pilots to operate at such low altitudes -- weather, mission, and threat (Miller, 1983:1-13).

The weather affects the tactical mission by forcing the pilot to a low altitude in order to fly under the ceiling. This may be necessary in order to obtain a visual acquisition of a target (Miller, 1983:1-13).

The next reason for utilizing low altitude penetration is mission. The mission of a tactical aircraft may dictate entering the low altitude envelope in order to carry out their assigned tasks. This may include delivering weapons in such a manner to ensure an acceptable probability of hitting the target.

The last reason for entering the low altitude envelope is to elude the air defense threats. The pilot may choose to fly at a low altitude to prevent or at least hinder the acquisition efforts of the air defense radar systems and to decrease the effectiveness of the enemy's weapon systems by limiting the exposure time of the aircraft to the weapons. The threat factor is considered the most important of the three when dealing with low altitude navigation (Miller, 1983:1-17). Threats cause the pilot to be concerned with preserving his life as well as completing the mission successfully. Thus, the pilot is presented with two life-threatening situations. The pilot must elude the threats and impact with the ground. The pilot will typically choose to concentrate his efforts on avoiding the threat instead of concentrating on navigating his aircraft in the low altitude envelope although navigating the aircraft has been proven to be the most lethal (Miller, 1983:1-17). Selecting to elude the threat over concerning himself with the low altitude issue is due to how the pilot perceives the situation at hand (Miller, 1983:1-17). However, the terrain clearance must be the primary task of the pilot (Miller, 1983:2-11). Consequently, the pilot is faced with two tasks that must be performed synergically. This can often lead to pilot saturation by forcing the pilot to operate beyond his cognitive capabilities. Perceiving the current environment

and exceeding the cognitive capacity of the pilot are addressed in the following sections.

Situational Awareness

Major Robert B. Bahnij, a former F-16 instructor pilot, stated "The primary goal of tactical aviation is mission accomplishment with force survival" (Bahnij, 1985:IV-1). A secondary goal of tactical aviation could be the effective use of available resources to achieve the primary goals. These resources typically include an electronic warfare sensor suite to control the electromagnetic spectrum as well as other electronic countermeasures for controlling the electromagnetic spectrum such as chaff and flares.

The sensor suite is characterized by several types of electronic countermeasure systems that span a vast frequency spectrum (Fitts, 1980). These systems must be allocated in concert with the other ECM resources such as chaff, flares, and decoys in order to effectively combat the air defense system. The ability to effectively allocate these resources during penetration of enemy air defense systems could legitimately be questioned.

Previous attempts to allocate these EW resources were commanded by an electronic warfare officer (EWO), the second crewmember of a two-seat fighter. However, with the trend in aircraft design tending toward smaller and faster fighters, the luxury of a second crewmember, the EWO, is

quickly compromised. However, the requirement to effectively allocate the EW resources still exists; therefore, the pilot is left with the task previously filled by the EWO. The pilot must divert his attention from the primary goals towards the secondary goals. As one would expect, this diversion of the pilot's attention degrades his ability to fulfill his primary goals.

This phenomenon of diverting attention away from the primary goals is commonly associated with poor or degraded situational awareness. Major Don Waddell defined situational awareness as "an assessment of a situation based on the best possible information" (Waddell, 1979). Waddell said the assessment of a situation is actually the perception of the current situation by the pilot. Bahnij expounded the significance of situational awareness in the following statement: "Situation awareness is the domain master all must serve" (Bahnij, 1985:IV-1). Since situation awareness is paramount for the pilot and is the perception of the current situation, the pilot must not be distracted from correctly perceiving the situation. One such distraction is the requirement to allocate EW resources to combat the enemy air defense systems.

Although the EW systems are designed to facilitate the successful completion of the mission, they demand the pilot's attention at the most inopportune time -- during penetration of enemy air defense systems. The pilot of a

single-seat aircraft is presented with a myriad of EW information that he is required to assimilate. The pilot is required to act as the integration component in the aircraft system and is typically overwhelmed by the volume of information he is required to process in order to locate, identify, and combat threats. Thus, the pilot cannot conceivably reason about how to allocate the EW resources of the aircraft to combat the various threats. The cognitive capacity of the pilot is exceeded and he is no longer capable of performing new tasks. This results in degraded situation awareness and a potential for compromising the mission.

Since some pilots feel the EW aspect is insignificant relative to the overall mission, the pilot will frequently deactivate the EW system in order to dedicate his complete concentration to the primary mission (Cross, 1987; Geiger, 1987). This defeats the purpose of electronic warfare and also may jeopardize the mission. Another solution to the dilemma of allocating EW resources is to provide an escort jammer or a stand-off jammer for the penetrating aircraft. Of course this places more aircraft in jeopardy. However, the pilot of the penetrating aircraft is now capable of dedicating significantly more attention to the task of flying his aircraft to the target area.

The following in-flight tactical mission scenario illustrates the EW complexities that must be considered during ground-based mission planning in order to obtain a complete and effective mission plan. A single-seat F-16 equipped with ECM pods is following its ingress route to a predesignated, high-valued target. The fighter is unescorted and is not supported by any other means of EW protection. The pilot is concentrating on successfully completing his mission and is relatively undistracted from this train of thought until the fighter approaches the forward edge of the battle area (FEBA).

Once the aircraft crosses the FEBA, the fighter is now within the battle area thereby placing more demands on the pilot. The pilot not only has to concentrate on completing the mission by flying to the target and dropping the munitions while providing ECM protection for himself but also on surviving the mission. As one would expect, the battle area is saturated with enemy air defense systems (Correll 1987:64; Schleher, 1986:337,349). The pilot must now evade the enemy defenses and complete the mission. These two aspects are competing for the attention of the pilot. The pilot can no longer disregard one aspect for the other and must apportion his attention to both issues. As the fighter penetrates deeper into the enemy's defenses and closer to his target, the aircraft encounters a denser threat environment (Fitts, 1980:33). This is natural for

the high-valued target to be protected by more threats. As the aircraft continues to penetrate the defense system, the pilot realizes he is being tracked by several radars. He decides to employ ECM jammers to confuse the threats. However, the threats are operating on widely separated frequency bands that are beyond the abilities of any one ECM jammer. The pilot must decide how and in what order to allocate his ECM resources in order to combat the different threats and synergically navigate his fighter to the target. Both of these tasks are intensive and require tremendous concentration to do well thereby causing the pilot to reach a point of task saturation where he is no longer able to assimilate any new information. While the pilot is considering the various constraints he must satisfy while planning his ECM strategy, a surface-to-air missile rose through the air toward the F-16. The pilot finally realizes the presence of the SAM and tries to evade the missile by ejecting flares. However, the pilot didn't realize he was flying into a corridor of anti-aircraft artillery fire while trying to avoid the missile. The aircraft was hit by the AAA fire and was destroyed.

Since the pilot in this scenario was preoccupied with avoiding the SAM missile by evasive maneuvers and applying ECM tactics while trying to navigate his fighter, he failed to detect the presence of AAA sites in his flight path. The pilot was a victim of degraded situation awareness.

Problems with Conventional Automation

With the air defense threat environment growing qualitatively and quantitatively, the penetrating tactical aircraft must be able to locate, identify, and combat these threats. This implies providing the pilot with the appropriate electronic systems to combat the threats. However, the typical response to this requirement is not always the best.

Conventional automation is the usual response to this requirement and is characterized by placing the new systems on the aircraft and provide the pilot the freedom to command the systems via cockpit controls and displays. However, there is an underlying problem with this approach. It forces the pilot to become the data integrator of the cockpit. The pilot must assimilate the incoming data into a working knowledge of the current situation which is in turn used to make the appropriate decision (Cross et al., 1986:143). This often results in degraded situational awareness. The pilot often becomes inundated with tasks in this environment (Cross et al., 1986:142).

Another problem with the conventional automation approach to these requirements is that conventional automation may try to remove tasks from the pilot's workload. Although this seems an obvious and beneficial answer to the problem of task saturation, some important information may be arbitrarily removed from the pilot's

assessment of the current situation thereby resulting in degraded situational awareness (Cross et al., 1986:142).

In order to overcome the problems associated with conventional automation, Major Steve Cross suggests a mix of the previously mentioned approaches to solving the information processing dilemma of the pilot. This fact is best illustrated in the following statement:

> ... automation must be applied in the appropriate amounts and in the appropriate areas to increase the pilot's performance capabilities. Automation should not arbitrarily remove tasks from the pilot. Rather, automation must be applied in ways that transform the cognitive processing required to perform certain tasks (Cross et al., 1986:142).

Furthermore, Cross proposes levels of automation. In fact, he decomposes automation into four levels. The various levels are characterized by the functions performed by the automation.

The first level provides the pilot with a means of performing the labor intensive computations required for mission planning such as fuel consumption and flying time.

The second level allows the pilot to modify his planned mission based on feedback from the computer. The computer uses knowledge about the mission to reason about how a violated constraint may affect other aspects of the mission.

Inflight automation differentiates the third level from the previous two. The pilot is capable of training his computer system to react to certain situations in a predesignated manner. This can include providing the pilot

with decision aids and system monitoring. The third level finds the computer performing contingency calculations such as allowing the pilot to perform his assigned task while solving secondary problems such as route selection based on fuel constraints.

The fourth level is characterized by having the computer perform functions previously accomplished by a second crewmember. The pilot and computer operate in concert. This level is also based on the fact that the computer has been trained by the pilot. The computer is capable of initiating problem solving based on some input from the diagnostic system of the aircraft. As such, the computer is capable of assuming greater cognitive responsibilities within the cockpit, thus affording the pilot the ability to focus his attention on high level mission goals. This has the benefit of increasing the pilot's situational awareness.

The conventional approaches to automation have been shown to be less than ideal for the tactical fighter. Conventional approaches require too much of the pilot. He is required to integrate disparate data into knowledge of the situation at hand in order to make decisions. As mentioned, a possible solution to this problem may be to train his systems to react to a situation. The pilot could program the cockpit systems to exhibit the desired behavior. This is similar to how a pilot interacts with a second

crewmember. The pilot and the crewmember train together, and as a result the crewmember learns the pilot's preferences. The pilot, in a sense, programs the crewmember (computer) to perform as the pilot would have him during missions.

Artificial Intelligence Issues

The concept of programming a computer to exhibit the characteristics of an expert is not new to the AI community. Several AI projects have been developed that are capable of programming a computer to perform as a expert would. In this case, the expert would be the second crewmember or the pilot. These AI programs are called expert systems.

An expert system could be developed capable of actually performing the tasks of the second crewmember. This is similar to the level four concept presented by Cross. As mentioned earlier, several fighter aircraft simply do not have the luxury of a second crewmember. This places increased burden on the pilot's cognitive abilities. An expert system would provide the pilot with significant information only when needed. This would help the pilot from becoming saturated with tasks.

The same principles can be applied to the ground-based planning that must occur just prior to a mission. The pilot must be capable of planning his route by fusing information obtained from various sources in a limited time period.

Additionally, the pilot must be able to reason about what threats he may confront, how he can combat the threats, and how probable is a fatal confrontation. A planning system can help here by assimilating the disparate information into knowledge about the environment, planning the route for the pilot, providing immediate feedback on how the air defense system is likely to reconfigure based on the current situation, and recommending changes to the flight plan. The planning system would, of course, contain the expertise of the pilots using the system.

Related Systems

The following systems represent previous efforts in planning systems as applied to the tactical mission planning domain as well as electronic warfare. The three planning systems are the Route Planning Aid (RPA), the Knowledge-Based System (KNOBS), and the Tactical Mission Planner (TMP).

RPA. The Route Planning Aid (RPA) was developed by Systems Control Technology, Inc. and was "designed to assist an F-111 pilot or mission planner in determining his 'best' ingress and egress routes from friendly airspace to a fixed, predesignated target, and returning" (Rockmore et al., 1983:1). The RPA considers the best route to be the route in which the probability of successfully evading the air defense systems and striking the target is the greatest.

The RPA is sectioned into three components: the Executive, the Optimization/Evaluation System, and the Knowledge-Based System. The Executive serves the purpose of user interface and control module for the planner. User interaction is menu-driven. The Optimization/Evaluation System can either derive or evaluate a route. The Knowledge-Based system accepts the output of the Optimization/Evaluation system and produces reasons why the route has its characteristics.

The RPA is capable of creating what it believes to be an optimal route for the given constraints as well as critiquing a user supplied route. The system critique is based on the lethality of the route. Because of this ability to critique a route, the RPA will undoubtedly benefit the pilot performing the planning operation. Feedback from the critiquing component of the RPA will provide the pilot with a measure of assurance that the selected route is in fact optimal. This increases the pilot situational awareness. The maximization of the mission flight path is accomplished using "a dynamic programming algorithm" (Rockmore, 1983:20). The algorithm decomposes the problem of constraint satisfaction for the aircraft given the mission scenario into simpler intermediate problems. This characteristic of the dynamic algorithm leads the reader to believe the algorithm is similar to a constraint-directed search of the same scenario. The

solution provided by the algorithm was compared to the solution of an exhaustive search and was found to be the same.

The RPA also performs terrain masking in order to provide the system with as realistic representation of the threat environment as possible. Additionally, the RPA performs threat analysis by maintaining a detailed threat lethality model of all threats.

The RPA system is run on a VAX minicomputer operating under the VMS operating system. The system uses two displays to convey the needed information to and from the user. A color graphics display is used for displaying map and route information. An alphanumeric display is used for user interface. The Executive and the Optimization/ Evaluation systems are written in Fortran, whereas the Knowledge-Based system is coded in INTERLISP. As a result, the RPA requires two jobs to be executing concurrently. The Executive communicates with the Knowledge-Based system by passing commands and responses using a shared file. Communication between the Executive and the Optimization/ Evaluation system is done using Fortran calls.

Although the RPA creates a route for the pilot and critics a route supplied by the pilot, the RPA does not seem to consider or reason about how to allocate the ECM resources of the aircraft in order to maximize the

survivability of the route. Nor does the RPA provide the pilot with a simulation of the plan in order to verify the planned route. These issues are addressed in this thesis.

KNOBS. KNOBS (Knowledge-Based System) is an experimental tactical air mission planning aid developed by the MITRE Corporation between 1978 and 1982 (Engelman et al., 1983:450). Originally, KNOBS was an interactive system designed to help an Air Force officer acting as a controller in a tactical air command and control center to plan a mission to attack a specific target (Engelman et al., 1980:184; Engelman et al., 1983:450). However, the term KNOBS has grown to refer to an architecture (Waterman, 1986:293) in which various expert systems have been developed to include such applications as planning the activity of the space shuttle crew to the loading of the cryogenic fuels into the Space Transportation System tanks (Engelman et al., 1983:450). When the term KNOBS is used in this thesis, the reference is to the original expert system used for mission planning.

The knowledge base of KNOBS is a frame implementation based on FRL (Frame Representation Language) developed at the Massachusetts Institute of Technology (MIT) (Engelman et al., 1980:184; Waterman, 1986:347). The frame implementation facilitates the use of inheritance and constraints. The main thrust of KNOBS is constraint satisfaction and maintaining knowledge consistency based on

the knowledge in the knowledge base (Engelman et al., 1980; Engelman et al., 1983). KNOBS also uses a rule-based inference system and incorporates a interactive natural language interface to the user (Engelman et al., 1983:450). One of the unique features of KNOBS is the implementation of interactive frame instantiation (Engelman et al., 1980; Engelman et al., 1983:456-457). The instantiation is handled by using templates similar to the instantiated frame. The information of the frame is supplied by the user.

The planning process of KNOBS is actually tasking the knowledge base to insure constraints of the mission are satisfied. For example, the aircraft from base X must be capable of delivering the weapons to the target and return safely to base. Planning a mission involves stepping through menus and filling in requested information into the mission templates (Engelman et al., 1983:452) until an Air Tasking Order (the ultimate product) is created (Engelman et al., 1983:451). The planning process involves creating multiple plans and ranking these plans based on how well they satisfy the constraints (Engelman et al., 1983:460-462).

Although the planning process of KNOBS creates plans for the mission, the true test of a plan is actually performing the plan and critiquing the results. This is often done using a simulation. A simulation would provide

immediate feedback to the mission planners on the feasibility of the plan given that the knowledge in the knowledge base is probably uncertain. This thesis addresses the issues of knowledge-based simulation and reasoning about uncertainty associated with the threat environment.

TMP. The Tactical Mission Planner (TMP) is an interactive planning system developed at the Air Force Institute of Technology (AFIT). This planning system was originally designed and developed by Major Robert Bahnij (Bahnij, 1985) and later modified by Lieutenant Jeffery Bradshaw (Bradshaw, 1986). The planner was designed for a pilot planning an offensive counter air tactical mission. This type of mission is characterized by dropping ordnances on a target (air to ground).

The TMP was developed to automate "many of the labor intensive, computationally demanding tasks now associated with tactical mission planning" (Bahnij, 1985). The TMP provides an environment where the pilot can concentrate on the higher aspects of the mission instead of the low-level tasks. This increases the pilot's situational awareness.

The TMP is a menu-driven interactive planning system. Menus are used extensively to provide an environment in which a pilot can learn quickly. The pilot generates the mission route interactively with the planner. In other words, the pilot is responsible for the mission route; it is not generated automatically by an algorithm. This allows

the pilot to brief himself as he plans the route. Since waypoint selection is the responsibility of the pilot, he will consider the threat environment during the route planning. Therefore, the pilot has a mental picture of the mission route as he plans it and situational awareness is increased. Routes generated using automatic means must be studied by the pilot and possibly explained as to why this particular route was chosen.

Once a mission route is planned by the pilot, the TMP performs fuel and time calculations to determine if the route violates either fuel (uses too much) or time constraints. If constraints are violated, the pilot has the capability to interactively alter the mission route.

The TMP is capable of representing two types of threats -- SAMs and AAAs. The threats are represented on a digitized map as circles. Based on the current intelligence information, the pilot can create the threat environment and store this environment to a file for future reference. Creating the threat environment is supported by allowing the pilot to place any threat type on the map in any location.

The TMP was developed on a Symbolics 3600 series lisp machine. A second monitor, a Symbolics high resolution color monitor, was used to display the terrain map as well as other important information. The system was developed using Zetalisp, Flavors, and Knowledge Engineering Environment (KEE) version 2.1 (Bahnij, 1985:IV-27 to IV-29).

This interactive planning system is used in this research as the planning interface to the pilot. The system has demonstrated merit in the field of tactical mission planning and is incorporated into this research.

Summary

This appendix has addressed the tactical mission planning aspect of this research. The tactical environment was discussed and why planning in this environment is so critical. Since this environment is so lethal, the pilot must maintain situational awareness of the environment. The problems of conventional automation were also discussed. Finally, the artificial intelligence issues that relate to this research was discussed as well as some related systems.

Appendix F: Uncertainty Representations

This appendix discusses the various techniques used to represent the uncertainty associated with different systems.

The most popular type of representation used to represent uncertainty is referred to by Paul Cohen as parallel certainty inferences (Cohen, 1985a:21). Paul Cohen described parallel certainty inferences as follows:

> At its most general, the technique splits reasoning in uncertain domains into two more or less dependent processes. In the first, conclusions are derived as if under certainty. In the second process, the goal is to decide how much the conclusions of the first process are to be believed (Cohen, 1985a:21-22).

Parallel certainty inferences typically associate a number with the corresponding conclusion. These numbers are usually between 0 and 1. However, some systems, MYCIN for example, have adopted a variation on this numbering scheme. MYCIN associates certainty factors (CF) to the conclusions, and these CF are between -1 and 1 to distinguish between levels of belief (1) and levels of disbelief (-1) (Shortliffe and Buchanan, 1984:247-252). These numbers are collectively referred to as degrees of belief (Cohen, 1985a:23) in this thesis.

The degrees of belief are divided into two types. The first type is called the initial degree of belief and is supplied by the domain expert during knowledge acquisition. The second type is the derived degree of belief and is

derived as the system infers its conclusions. The derived degrees of belief are further decomposed into two operations. The first updates the degree of belief of a hypothesis given new evidence enters the system and is commonly referred to as pooling evidence. The second operation is for updating the degree of belief of a conclusion given the uncertainty of the associated hypotheses and is commonly referred to as propagating (Cohen, 1985a:23-25). These two operations, pooling and propagating, are called combining functions (Cohen, 1985a:26).

The remainder of this appendix will discuss the various pooling combining functions devised by different researchers. Each combining function is presented in sufficient detail to acquaint the reader with the basic concepts of the different functions. More specifically, the following combining functions are presented: the Bayesian theory, the Dempster-Shafer theory of evidence, fuzzy logic, and finally the theory of endorsements.

Bayesian Approach

The first combining function discussed is the Bayesian approach. The Bayesian approach uses Bayes' theory which was first introduced in 1763 by Reverend Thomas Bayes (Larsen and Marx, 1986:55). Conditional probability underlies the Bayesian approach and is the probability an

event will occur given another event has occurred. To cast this definition in terms of an expert system, the definition could be the probability of a hypothesis will occur given some pieces of evidence that may support the hypothesis. The following example, taken from Larsen and Marx (Larsen and Marx, 1986:43), illustrates conditional probability: A card is drawn from a standard poker deck. What is the probability the card selected is a club given the card is a king? The definition for conditional probability will provide an answer to this question and is defined (Larsen and Marx, 1986:43) as the relation

$$P(C|K) = \frac{P(C \text{ and } K)}{P(K)} \tag{1}$$

where

P(C|K) = probability the card is a club given it is a king
P(C and K) = probability the card is the king of clubs
P(K) = probability the card is a king

Given P(K) is 4/52 and P(C and K) is 1/52, the P(C|K) can be shown to be 1/4.

Using the form of the conditional probability equation, Eq (1), a general form of Bayes' theorem is derived:

$$P(h|e) = \frac{P(e|h)P(h)}{P(e)} \tag{2}$$

where

P(h|e) = probability of hypothesis given evidence
P(e|h) = probability of evidence given the hypothesis
P(h) = probability of hypothesis
P(e) = probability of evidence

This form of Bayes' theorem is typically inadequate for use in expert systems (Cohen, 1985a:28) because this form only allows one hypothesis and is limited to reasoning over a single piece of evidence. Therefore, Eq (2) is extended to include several hypotheses and pieces of evidence:

$$P(h_i | e_1 \& \ldots \& e_m) = \frac{P(e_1 \& \ldots \& e_m | h_i) P(h_i)}{\sum_{j = 1 \text{ to } n} P(h_j) P(e_1 \& \ldots \& e_m | h_j)} \quad (3)$$

Eq (3) (Cohen, 1985a:29) assumes that the n hypotheses are mutually exclusive and exhaustive. The denominator also implies the a priori knowledge of all possible combinations of evidence and hypotheses (Cohen, 1985a:29). This assumption is often not practical in most applications and requires yet another assumption to relieve. This new assumption is conditional independence and is characterized by the fact that "the probability of the intersection of two independent events is equal to the product of their individual probabilities" (Larsen and Marx, 1986:60). This can be seen in the card example. The probability of drawing a club from the deck is always 1/4 regardless of its face value. The two events, a club and a king, are independent in this example. Independence reduces Eq (3) to

$$P(h_i | e_1 \& \ldots \& e_m) = \frac{P(e_1 | h_i) \ldots P(e_m | h_i) P(h_i)}{\sum_{j = 1 \text{ to } n} P(h_j) P(e_1 | h_j) \ldots P(e_m | h_j)} \quad (4)$$

Eq (4) (Cohen, 1985a:30) is the form of Bayes' theorem commonly used.

Although Bayes' theorem seems to satisfy all requirements for pooling the evidence, it is not a panacea; it does have serious problems. Some of the more serious issues are addressed here. The assumptions of mutual exclusive and exhaustive hypotheses and conditional independence are not always true (Cohen, 1985a:30; Szolovits and Pauker, 1978:121). Another serious problem with the Bayesian approach is its "voracious demand for data" (Szolovits and Pauker, 1978:120; Stefik et al., 1983:94). Large amounts of conditional and a priori probabilities are required for Bayesian inferences (Lesmo et al., 1985:311; Adams, 1984:263; Rich, 1983:192). Before conditional independence was assumed, the denominator of the Eq (3) would require 2420 computations if the problem only had 10 hypotheses and 5 binary tests (Szolovits and Pauker, 1978:120). Assuming conditional independence decreased the number of computations to 100 (Szolovits and Pauker, 1978:121). Other problems include the inability of the approach to distinguish between uncertainty and ignorance (Cohen, 1985a:31). Also, the precision of the single degree

of belief is not known, and the reasons for believing and disbelieving are combined into a single number (Cohen, 1985a:31). Additionally, modifying the database would prove to be very difficult due to the interactions between components (Rich, 1983:192).

These problems discussed here are significant enough to limit the Bayesian approach to "small well-constrained problem domains" (Szolovits and Pauker, 1978:122). Some of the problems found in the Bayesian approach are overcome by specific implementations. For example, MYCIN is based on Bayesian theory (Adams, 1984:264-271; Bonissone and Tong, 1985:245) and has overcome the problem of a single number representing both the level of belief and the level of disbelief by using a measure of belief (MB) and a measure of disbelief (MD) (Shortliffe and Buchanan, 1984:247-262).

Dempster-Shafer Theory of Evidence

The Dempster-Shafer theory was first introduced by Arthur Dempster in 1967 and later modified by Glenn Shafer in 1976 (Bonissone and Tong, 1985:245). The Dempster-Shafer theory of evidence provides a means of representing uncertainty unknown to the Bayesian approach. Although both theories represent uncertainty with degrees of belief, the Dempster-Shafer theory has a significant advantage over Bayes' theory; a degree of belief is associated with subsets of hypotheses in the Dempster-Shafer theory. This allows

reasoning about sets of hypotheses and is not limited to the singleton hypotheses as required in Bayes' theorem.

The following example illustrates the power of the Dempster-Shafer theory and is similar to the example given by Cohen (Cohen, 1985a:37-40). The air defense system of the Soviet Union is used to illustrate this theory. This defense system is composed of several different defensive weapons. Surface-to-air missiles (SAM) and anti-aircraft-artillery (AAA) are the primary threats incorporated into this defense. For the sake of illustration, only two SAM's, SA-1 and SA-2, and two AAA's, AAA-1 and AAA-2, are assumed to be operational. An F-16 fighter aircraft is trying to penetrate these defenses and is confronted with several different hypotheses about which defense will destroy the aggressor aircraft. Besides the four individual (singleton) hypotheses, three additional hypotheses exist and are cleanly represented under this theory: the SAM's will destroy the aircraft, the AAA's will destroy the aircraft and one of the four will destroy the aircraft. This ability to assign probabilities to sets is easily handled in this theory; whereas, the Bayesian theory falters.

After reading the current intelligence information, the pilot knows the probability of being shot down by a SAM site is .3. This is represented in the Dempster-Shafer theory by assigning the .3 probability to the set {SA-1 SA-2} without dividing the .3 between the two singletons. This is not

possible with Bayes' theorem; the .3 would have to be divided between SA-1 and SA-2 giving the illusion of knowing more about which defense will destroy the aircraft than actually known. Additionally, the remaining .7 (1 -.3 = .7) would have to be distributed between AAA-1 and AAA-2. Once again, this presupposes more knowledge than is actually available. This theory allows the remaining .7 to be assigned to a set of all singletons {SA-1 SA-2 AAA-1 AAA-2} called the frame of discernment (Θ). The singletons that comprise Θ are assumed to be mutually exclusive and exhaustive (Cohen, 1985a:38; Gordon and Shortliffe, 1984:273). The frame of discernment "reflects our ignorance about which singleton is true" (Cohen, 1985a:38). As mentioned earlier, Bayes' theorem is unable to represent ignorance. If the intelligence information is unavailable to the pilot before his mission, Θ is 1.0 representing complete ignorance of the threats.

The basic probability assignment (m) assigns probabilities to the subsets, including singletons, of Θ and "is a generalization of the traditional probability density function" (Gordon and Shortliffe, 1984:275). For this example, m({SA-1 SA-2}) = .3 and m({Θ}) = .7. The quantity m(Θ) is the remaining probability after all probabilities are assigned to the subsets.

A belief function (Bel) is used as a measure of the total amount of belief in a hypothesis. For example, if m({SA-1}) = .2 and m({SA-2}) = .1, the total belief in the hypothesis is Bel({SA-1 SA-2}) = m({SA-1}) + m({SA-2}) = .3. Dempster's rule of combination (⊕) is the combining function used by this theory. The actual combination is simply a multiplication of the various hypotheses. This rule provides a mechanism to compute new probability assignments and new belief functions.

Before departing the briefing room, the pilot discovers some new evidence about the treats. This new evidence is m1({SA-1 AAA-1 AAA-2}) = .9. The pilot combines this evidence with his current evidence m2({SA-1 SA-2}) = .3 and decides to avoid the SAM threats. His reasoning is represented in Figure 24:

		m2	
		{SA-1 AAA-1 AAA-2}(0.9)	Θ(0.1)
m1	{SA-1 SA-2}(0.3)	{SA-1}(0.27)	{SA-1 SA-2}(0.03)
	Θ(0.7)	{SA-1 AAA-1 AAA-2}(.63)	Θ(0.07)

Figure 24. Dempster-Shafer Reasoning Process

The entries in the table are simply the intersection of the two sets, and the probability assignments of the intersections are the probability assignments of the

original sets multiplied together. For example, the intersection of {SA-1 AAA-1 AAA-2} and {SA-1 SA-2} is {SA-1}, and the assigned probability is m1⊕m2({SA-1}) = 0.27. The remaining assignment probabilities are calculated in the same manner. The belief functions are calculated similarly. The belief that a SAM will destroy the aircraft is illustrated in Figure 25.

```
Bel1⊕Bel2({SA-1 SA-2}) = m1⊕m2({SA-1 SA-2})
                          + m1⊕m2({SA-1})
                          + m1⊕m2({SA-2})

                        = 0.03 + 0.27 + 0
                        = 0.3
```

Figure 25. Dempster-Shafer Belief Functions

Although the Dempster-Shafer theory seems to solve all the problems of representing uncertainty in a system, several problems prevent this theory from actually being implemented into an expert system (Lesmo et al., 1985:310). The paramount problem is the computational complexity of the implementation (Shafer, 1985:16; Bonissone and Tong, 1985:245); calculating the degrees of belief "requires time exponential in the cardinality of the hypothesis set" (Bonissone and Tong, 1985:245).

Fuzzy Logic

Fuzzy logic was introduced by Lotfi Zadeh and is based on the theory of fuzzy sets (Stefik et al., 1983:94-95).

Fuzzy logic provides a means of representing the inherent vagueness of language. For example, what is the height of a tall person? Is a tall person 5 feet tall? Fuzzy logic allows the vagueness to be represented as illustrated in the following example: Bill is tall. The fuzzy representation of this statement may be

(Bill is an element of (0, 4), 0.1)
(Bill is an element of (4, 5), 0.3)
(Bill is an element of (>5), 0.6)

This example illustrates the vagueness associated with tall. Objects have a degree of membership associated with each set. The uncertainty is represented by possibility instead of probability. A membership function is used to calculate the possibility of a statement.

Although the concepts of fuzzy logic and possibility theory have been present for several years, few systems have been implemented using these concepts (Cohen, 1985a:42). This precludes any meaningful evaluation of the techniques.

The Theory of Endorsements

Finally, the last technique presented in this appendix is the theory of endorsements. This theory was first proposed by Paul Cohen in 1983 and "is based on a purely qualitative theory of endorsements" (Bonissone and Tong, 1985:246). The theory of endorsements attempts to solve the problems associated with representing uncertainty by using numbers. Cohen (Cohen and Grinberg, 1983b; Cohen, 1985b)

points out some of the problems with using numbers to represent uncertainty in a system. Some of the more significant problems are discussed.

A few of these problems have already been presented earlier in this chapter such as losing precision of the uncertainty and the single number combining reasons for believing and disbelieving. Paramount among the concerns of numerical representation is that the numbers "hide the reasoning that produces them and thus limits one's reasoning about uncertainty" (Cohen and Grinberg, 1983b:17). Several other concerns exist for representing uncertainty with numbers and are not discussed; a complete analysis of these problems is beyond the scope of this thesis.

An endorsement is "the explicit marking of factors relating to one's certainty" (Cohen and Grinberg, 1983b:21) and is similar to the functional operation of a bureaucracy. Each lower level bureaucrat must endorse a piece of work before it proceeds up the chain of command (Cohen and Grinberg, 1983b:21). In the context of expert systems, endorsements are simply a record of reasons for believing and disbelieving a hypothesis produced by inferences (Cohen and Grinberg, 1983b) and "classify the justification according to the type of evidence (for and against a proposition)" and "the possible actions required to solve the uncertainty of that evidence" (Bonissone and Tong, 1985:246).

This theory requires the endorsements to be ranked. The ranking is not as simple as the numerical counterpart; the ranking depends on the context in which the conclusion is required. For example, convicting a criminal may be easier if the witness is the mayor of the town as opposed to the town drunk. The mayor's testimony is preferred over the drunk's. That is to say "a conclusion endorsed as having the one kind of evidence for its support is more than a conclusion endorsed as supported by less preferred evidence" (Cohen and Grinberg, 1983a:356). Cohen points out the ranking of the endorsements requires much knowledge (Cohen and Grinberg, 1983a:356). This presents the problem of the implementation of the ranking mechanism; this mechanism must be specified for each particular context (Bonissone and Tong, 1985:246).

Heuristics are used to propagate the endorsements over the inferences. The propagation is performed using a set of rules (Cohen and Grinberg, 1983a:356). The endorsements associated with the premise are propagated to the conclusion. Propagation of endorsements requires "numerous idiosyncratic rules" (Cohen and Grinberg, 1983a:356). In fact, local combining functions are required for each context (Cohen and Grinberg, 1983b:24; Bonissone and Tong, 1985:246).

The theory of endorsements provides "a good mechanism for explanation, since they create and maintain the entire history of justifications" (Bonissone and Tong, 1985:246).

The theory of endorsements is an alternative to numerical representation of uncertainty. The theory has several intriguing properties; however, the problems discussed seem to be significant enough to warrant a close inspection of this theory before being implemented in a specific domain.

Representation Considerations

Parallel certainty inferences were presented as the most popular implementation of handling uncertainty. None of these approaches are the answer to the knowledge engineer's dilemma of how to reason about uncertainty. Bonissone and Tong summarize this dilemma best by stating "the uncertainty of evidence or facts is a complex object, and it is unlikely that a single, uniform representation will ever be sufficient to model it" (Bonissone and Tong, 1985:246). Each domain must be carefully studied to select the best representation. Some researchers (Bonissone and Tong, 1985:246) have proposed combining some of the different approaches to benefit from the assets of each.

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Abstract

A ground-based tactical mission planning system is presented which increases the situational awareness of a pilot planning an Offensive Counter Air attack mission (air-to-ground). The system automates many labor-intensive tasks associated with tactical mission planning such as fuel and time calculations. This system also provides a rich development environment for an electronic warfare engineer designing new electronic countermeasure (ECM) strategies. Artificial intelligence (AI) techniques are incorporated to increase the user's understanding of the threat environment and how to effectively apply ECM techniques.

Planning a tactical mission is best performed using interactive means to increase the situational awareness of the pilot by keeping him in the planning process. Similarly, ECM strategies are best developed in an interactive mode to allow the engineer the greatest degree of design freedom. However, these two individuals are only capable of exploiting local knowledge of threats (e.g. constraints about the most effective ECM strategy to use against threats). Consequently, global knowledge about the domain is not available to guide the planning process. Additionally, the inherent uncertainty of threat intelligence data complicates the planning process.

This thesis is an investigation of the novel integration of four explored ideas to produce a system that addresses these problems. These ideas are:

1. a prototype, interactive, ground-based, tactical mission planning system developed for F-16 pilots of the 17th Air Force,

2. an ECM strategy generation module based on local constraints associated with threats that is patterned after the constraint-directed search techniques applied by Fox for job-shop scheduling,

3. an object-oriented simulation patterned after ROSS to evaluate the effectiveness of the ECM strategy, and

4. a technique of reasoning about uncertainty to evaluate the ECM strategy.

This research demonstrates the feasibility of using AI techniques to develop an effective ground-based tactical mission planner.